Status Report and Proposal for EIC Calorimeter Development

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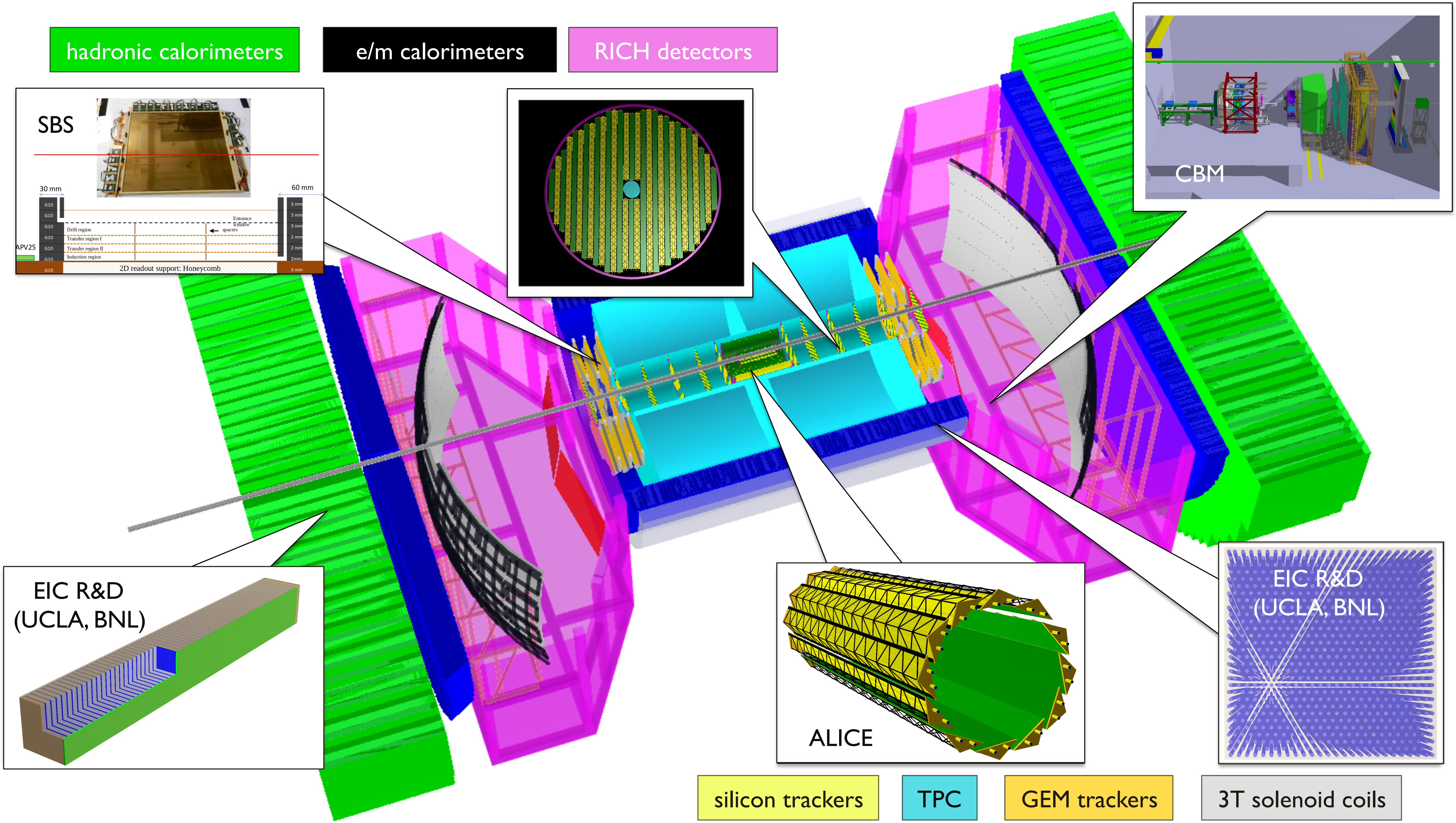
for eRD1 Consortium

BNL, EIC R&D Meeting, July 9 2015

Calorimeters as a part of a ‘perfect’ optimized EIC detector model.

Central Detector: close to 4π acceptance, reach in kinematic variables, reliable electron identification, good hadron PID, high spatial resolution of primary vertex, low material budget.



https://wiki.bnl.gov/eic/index.php/Detector_Design_Requirements

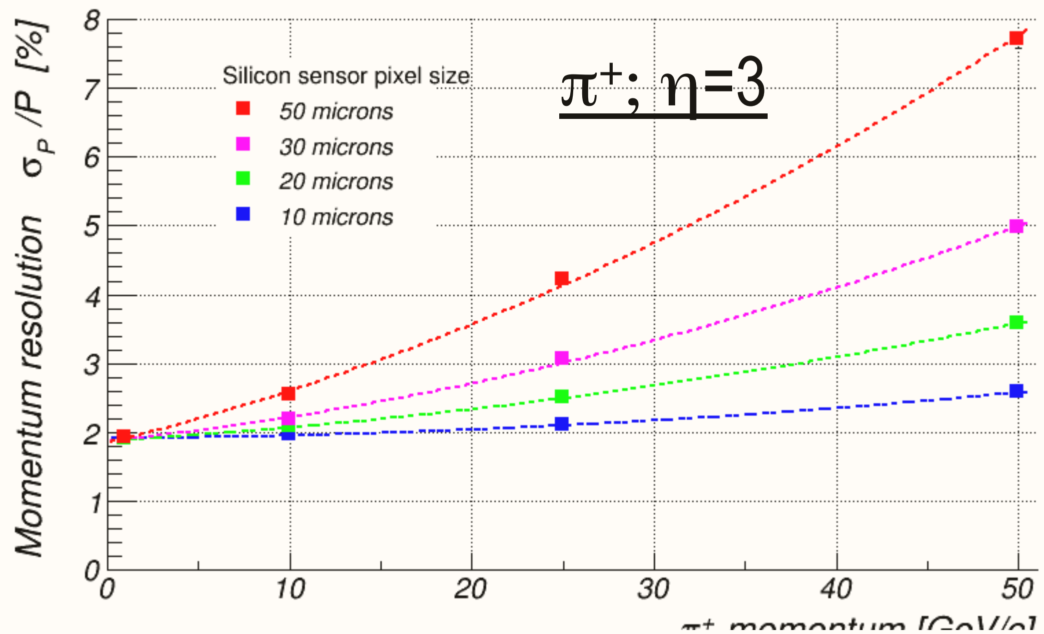
and in arXiv: 1108.1713, 1212.1701 and 1409.1633

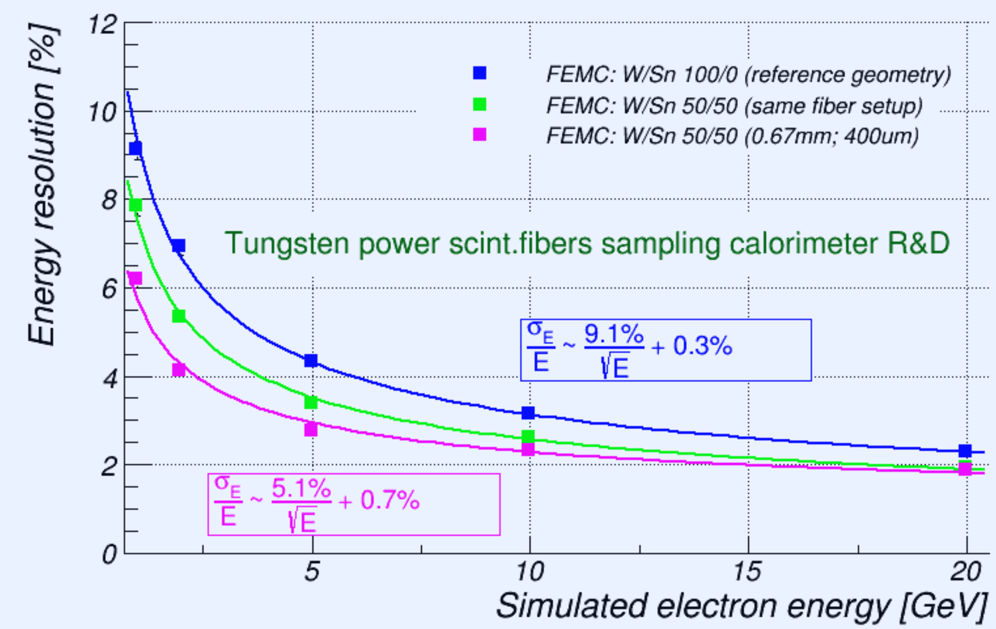
E.C. Aschenauer, A. Kiselev, R. Petti

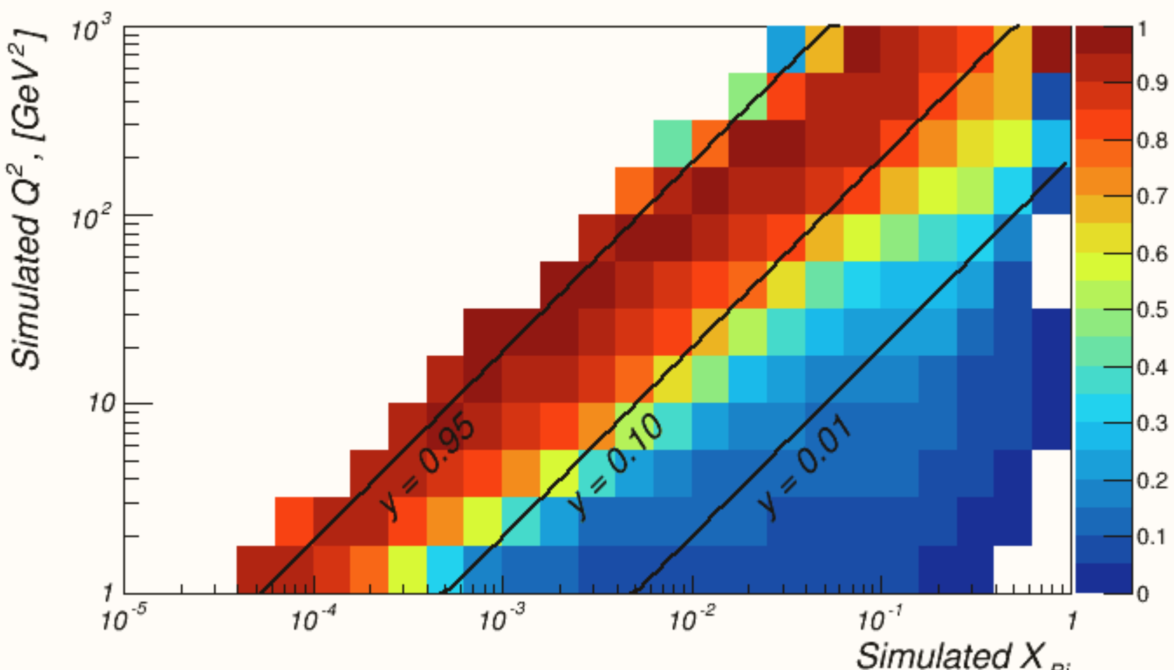
Optimization. Tracking and Calorimetry at backward region (example):

$$Purity = \frac{N_{gen} - N_{out}}{N_{gen} - N_{out} + N_{in}}$$

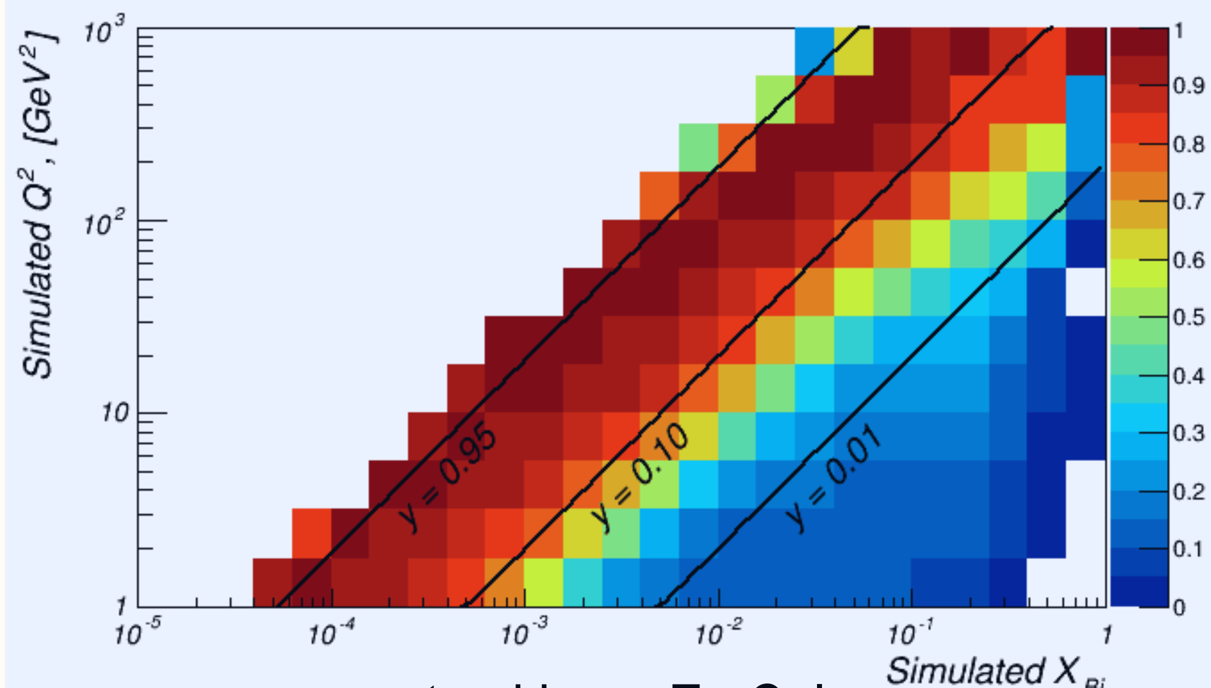
- Combined Calorimeter and Momentum resolution in x-Q2 bins > 60% for 0.01 < y < 0.95







tracking only

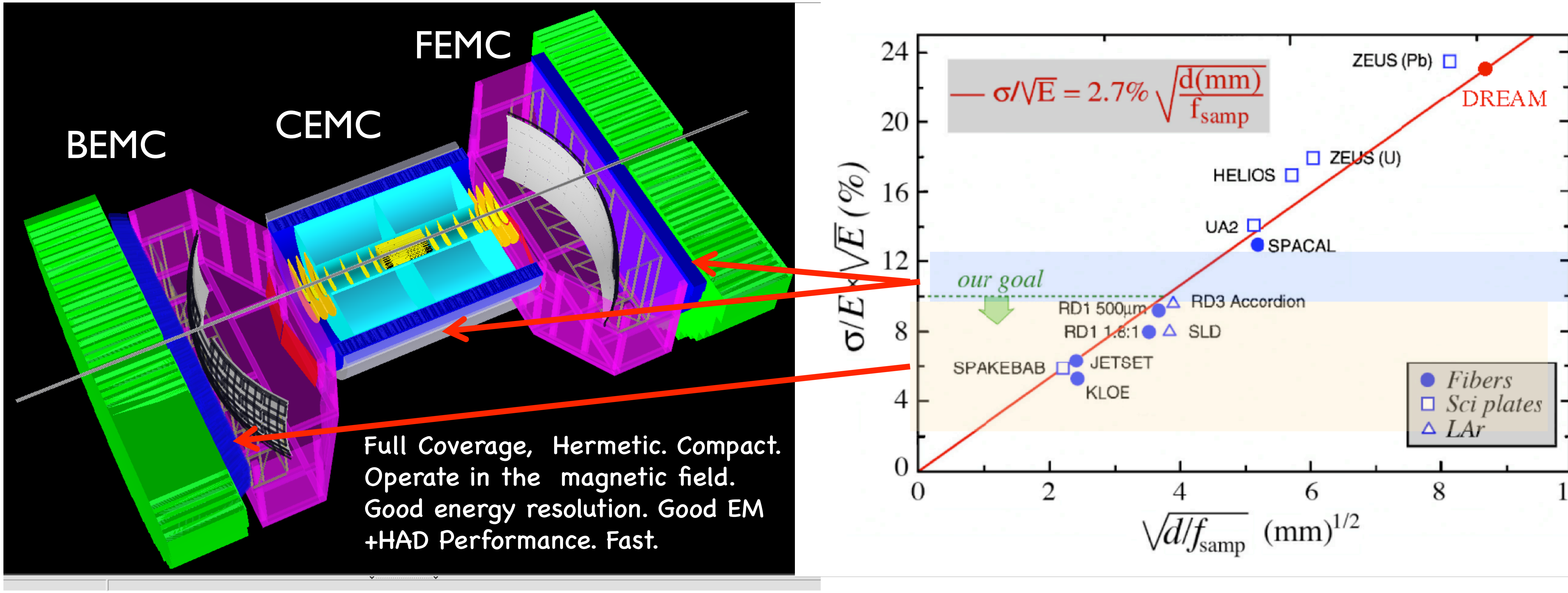


tracking + EmCal

- “Straightforward” tracking can hardly help at Y<0.1
- A good EmCal clearly helps to extend useful Y-range

A.Kiselev, DIS 2015

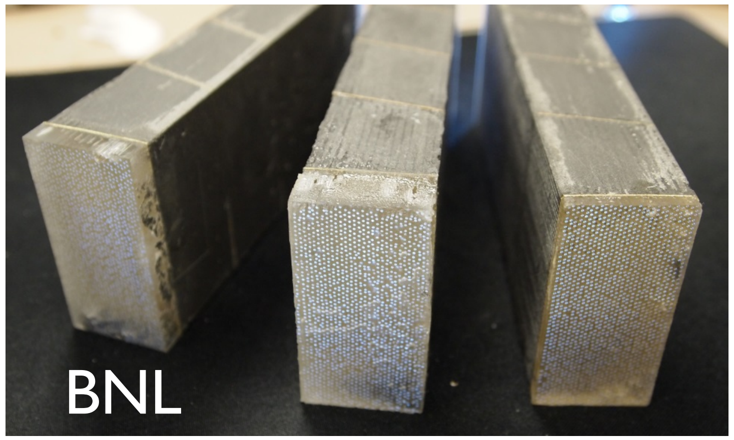
Areas of calorimeters R&D in 2015.

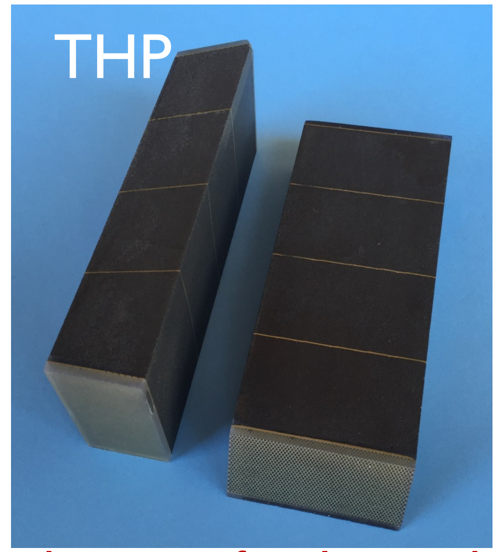


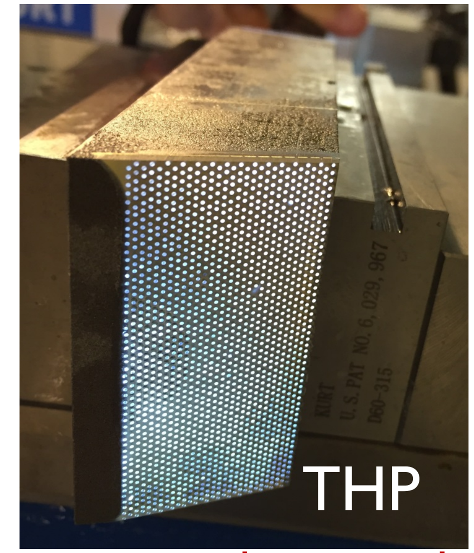
- Continue technology development for W powder ScFi emcal. Industrialization, push of technology for high resolution calorimetry, true projectivity (BEMC, CEMC, FEMC).
- Evaluation of SiPMs as a readout sensors. Radiation hardness (BEMC, CEMC, FEMC).
- Development of crystal calorimetry for EIC (BEMC).
- Collaboration with EIC simulation group. Refinement of calorimeter requirements and quantitative estimate of EIC radiation environment (BEMC,CEMC,FEMC).

What was achieved (general technology development):

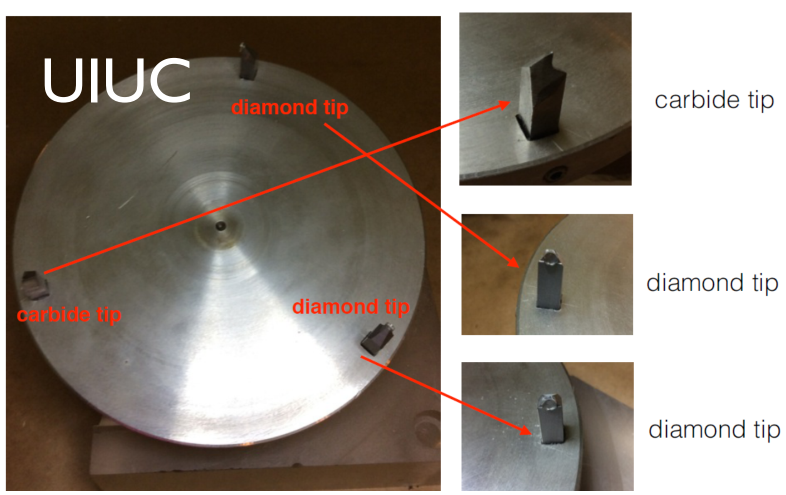
- Technology transfer from UCLA to UIUC, BNL, THP (industrialization). Relevant to CEMC, FEMC (energy resolution ~10%/sqrt(E)).







This was mainly a learning exercise in order to become familiar with the construction technique which will then be used to build fully projective modules.



Cutting and polishing ends of module with diamond fly cutter at UIUC.
(one of the first ScFi calorimeter was built by D.Hertzog there)

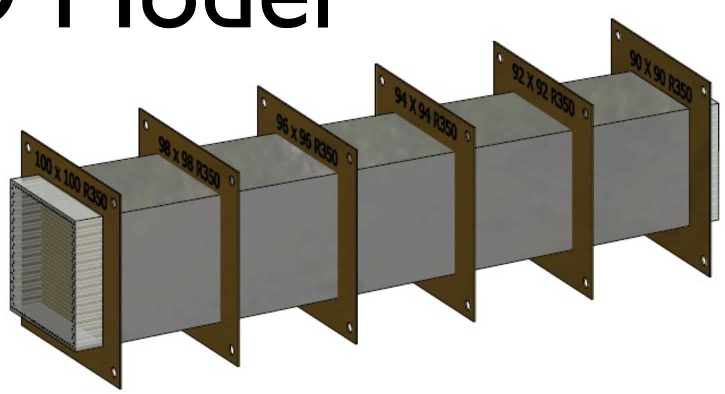
Latest UCLA 'HR' prototype will be sent to UIUC to re-work both ends of the detector with this fly cutter next week.

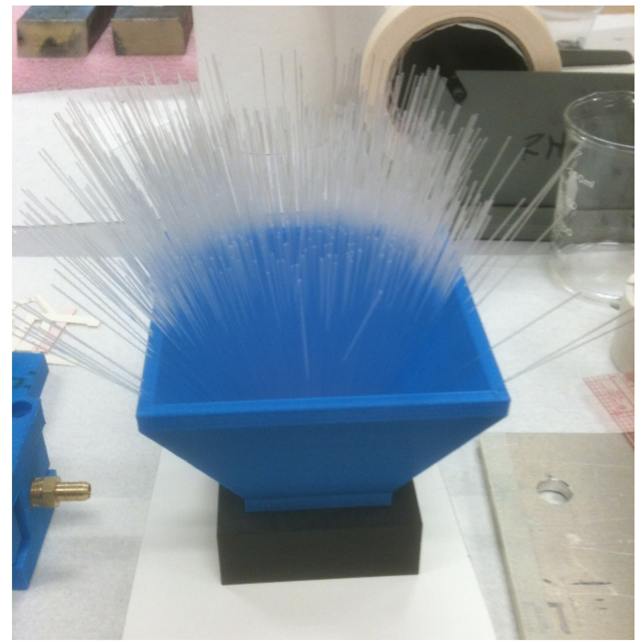
One of the goal at start of W/ScFi R&D project was to developed simple technology so that universities groups can easily adopt it. Now it started to materialize.

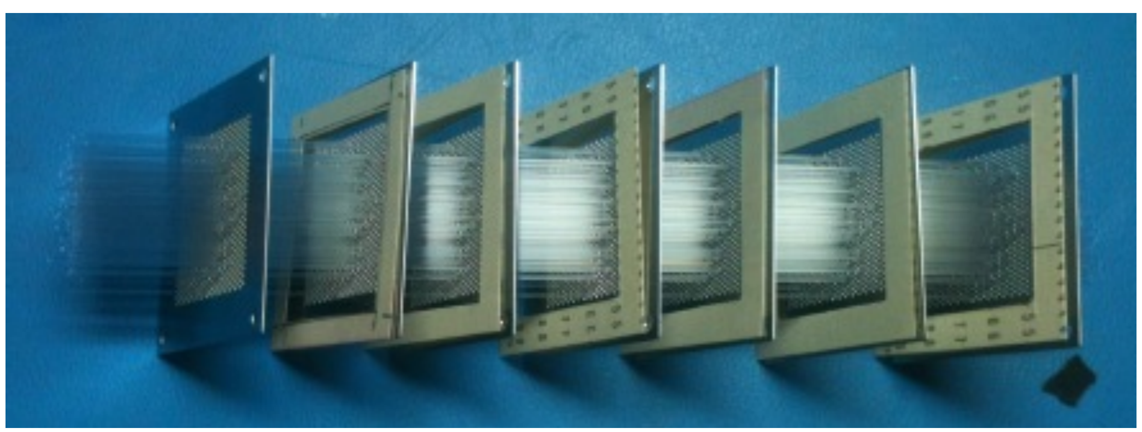
W/SciFi Module Production at BNL

Preparations to Construct Double Tapered Modules

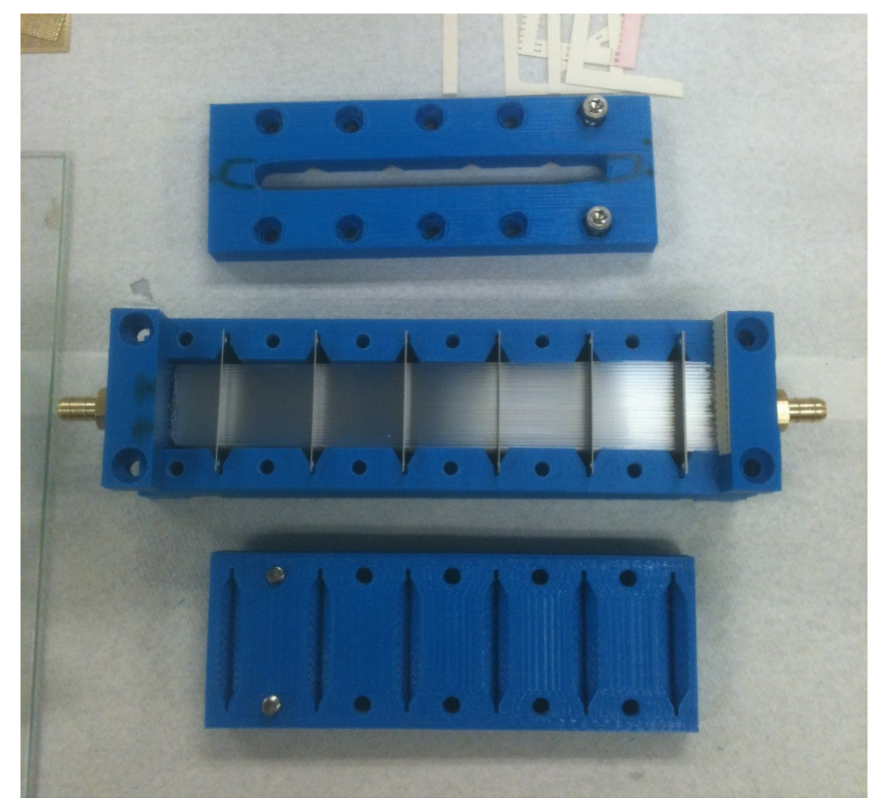
3D Model







Fiber assemblies in molds



Procedures for producing fully projective double tapered modules for the sPHENIX experiment are being developed by groups at BNL and UIUC. However, these same procedures should be applicable for producing other types of W/SciFi modules in a simple, cost effective way.

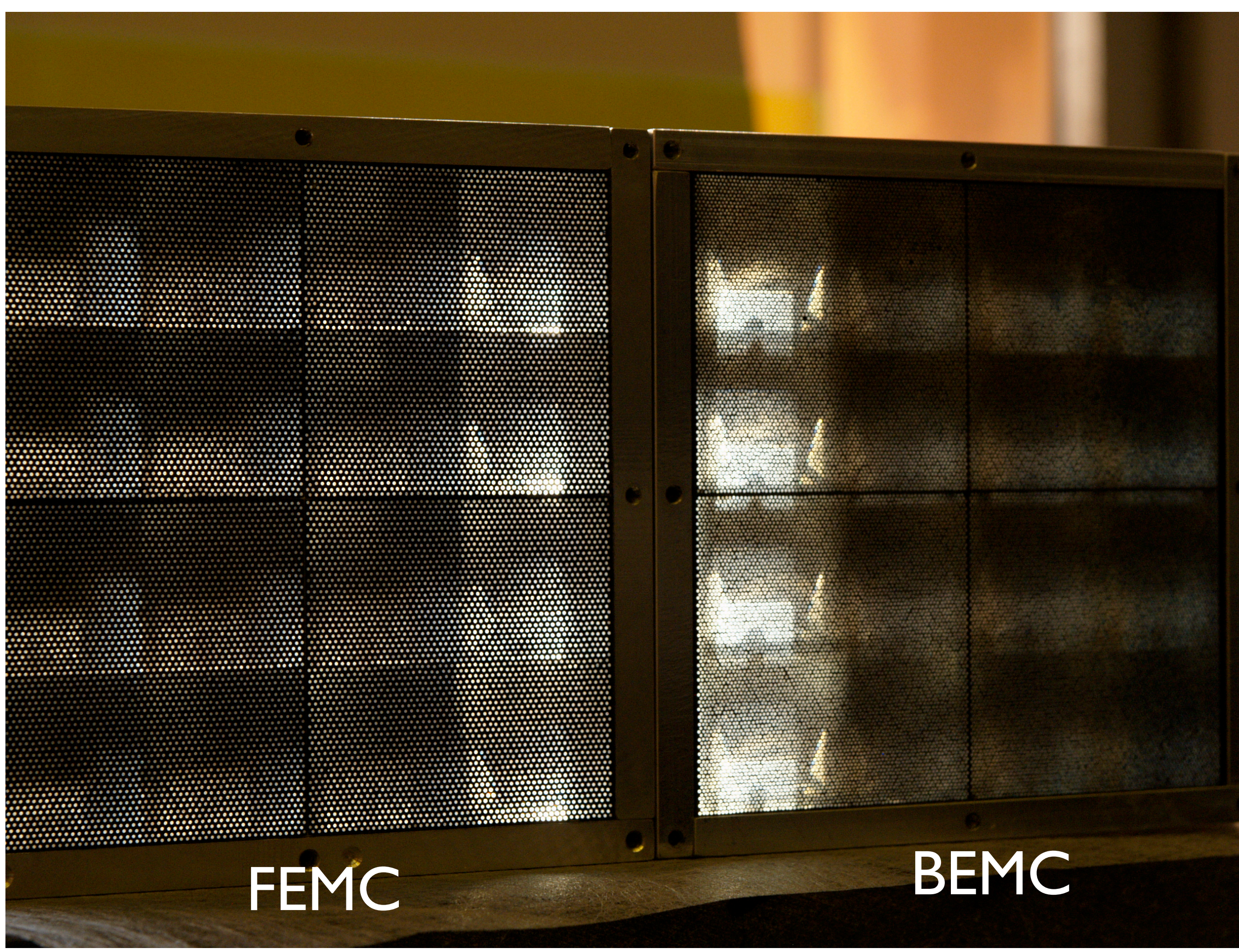
Sampling BEMC:

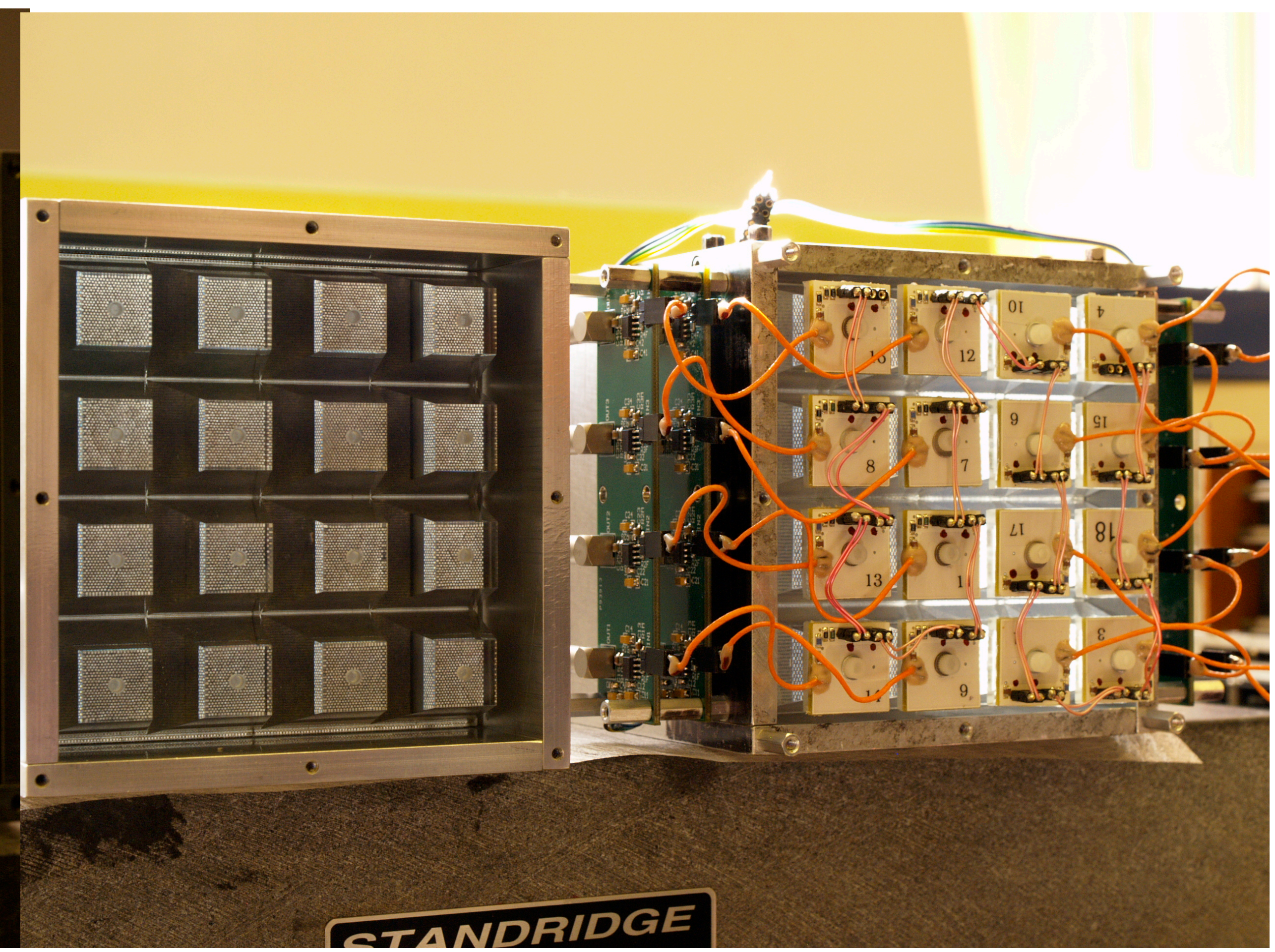
Investigate W/ScFi technology for high resolution EMCals (~6-7%/sqrt(E))

We increased sampling fraction and sampling frequency (0.667 mm center to center, fibers 0.4 mm in diameter, diluted absorber W 75%, Sn 25%).

Things that we were worried about:

- Handling of (25k) thin long fibers during packing through set of screens – OK
- Mould release due to increased length of the detector (25 cm) – OK
- Thermal runaway of epoxy during curing – OK





Test Run 2015 FNAL, May 19-29(UCLA, BNL, TAMU, PSU):

New BEMC Prototype

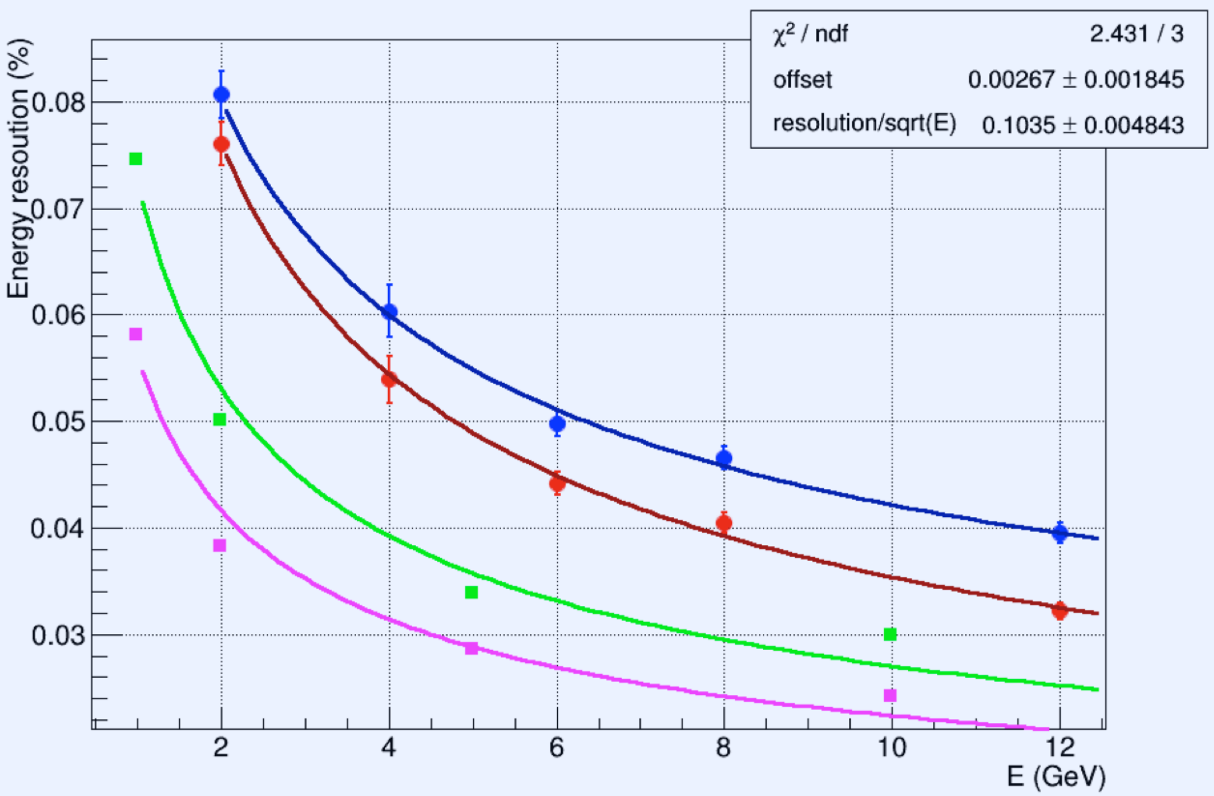


Figure 3 Energy resolution in EM prototype compared with MC predictions.

Magenta – Ideal MC for Test Beam prototype.
Green -Ideal MC + 460 p.e./GeV
Blue – raw experimental data.
Red – dp of beam subtructed

- Light Yield 460 p.e./GeV vs expected 900 p.e./GeV
- Big difference between expected (Green curve) and measured (Red curve), not yet explained.

Old FEMC Prototype with New light collection scheme

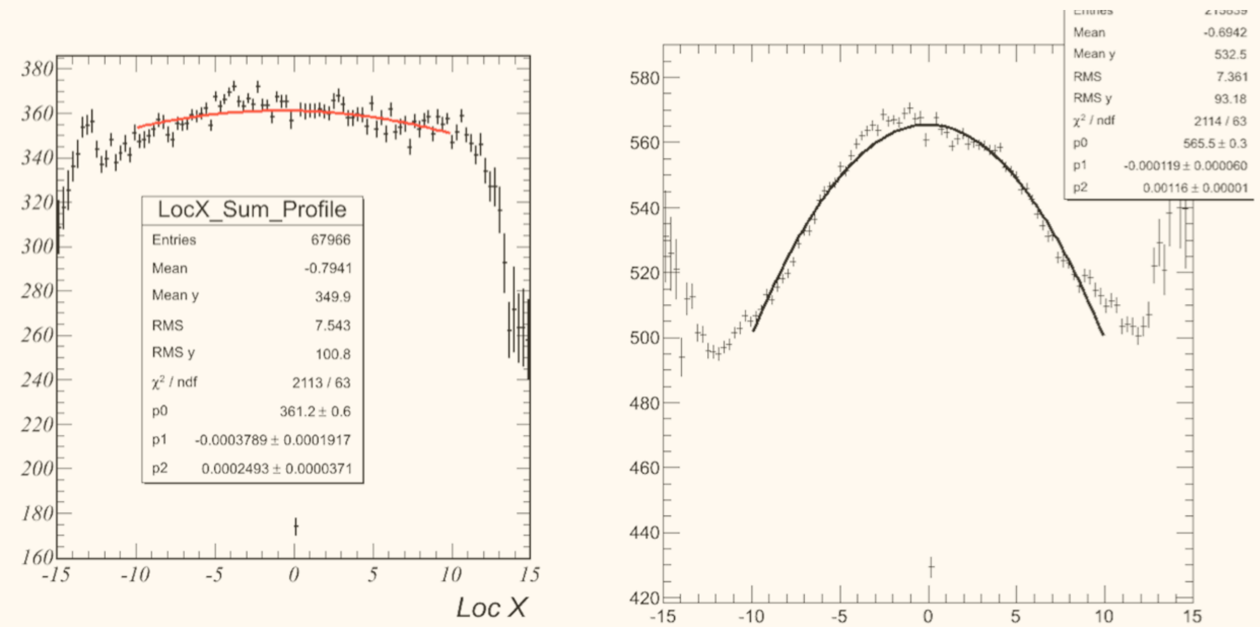


Figure 6. Response of the old EMcal to 4 GeV vs impact point. Left 2015 data, right 2014 data.

- Compensation filter between fibers and SiPMs did flatten response as expected
- Light loss 30% vs 15% as was expected

Test Run 2015 FNAL, no smoking gun found except low LY:

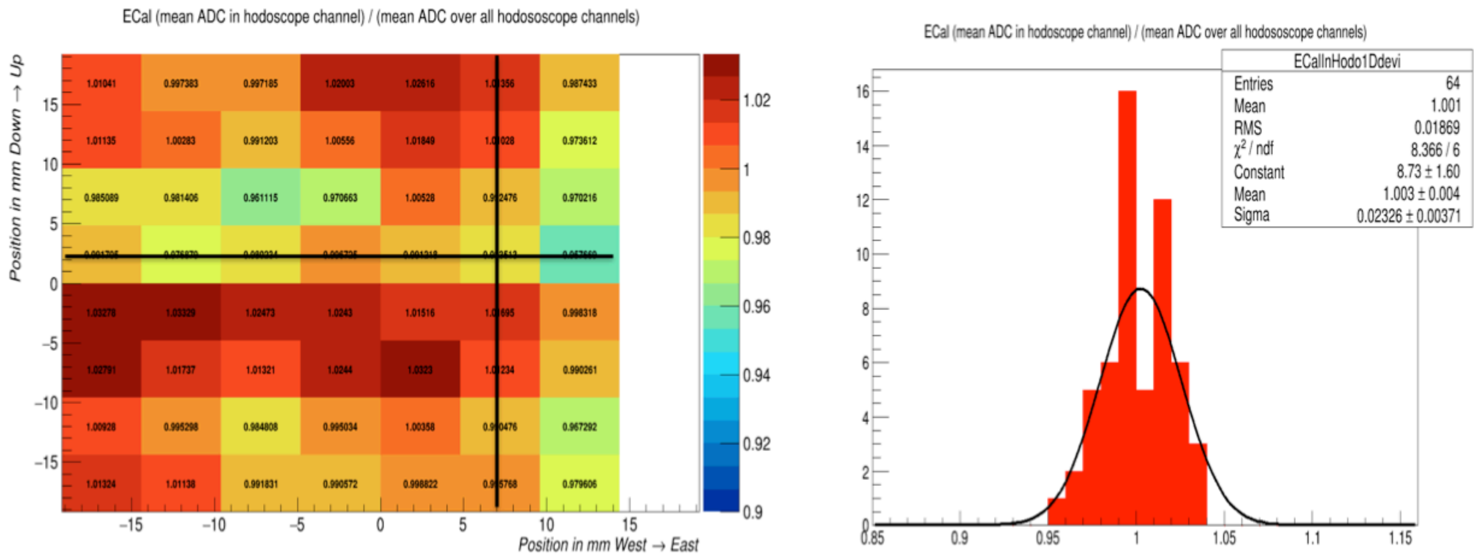


Figure 5. The uniformity of response across the face of the detector is 2.3% for 4 GeV electrons.

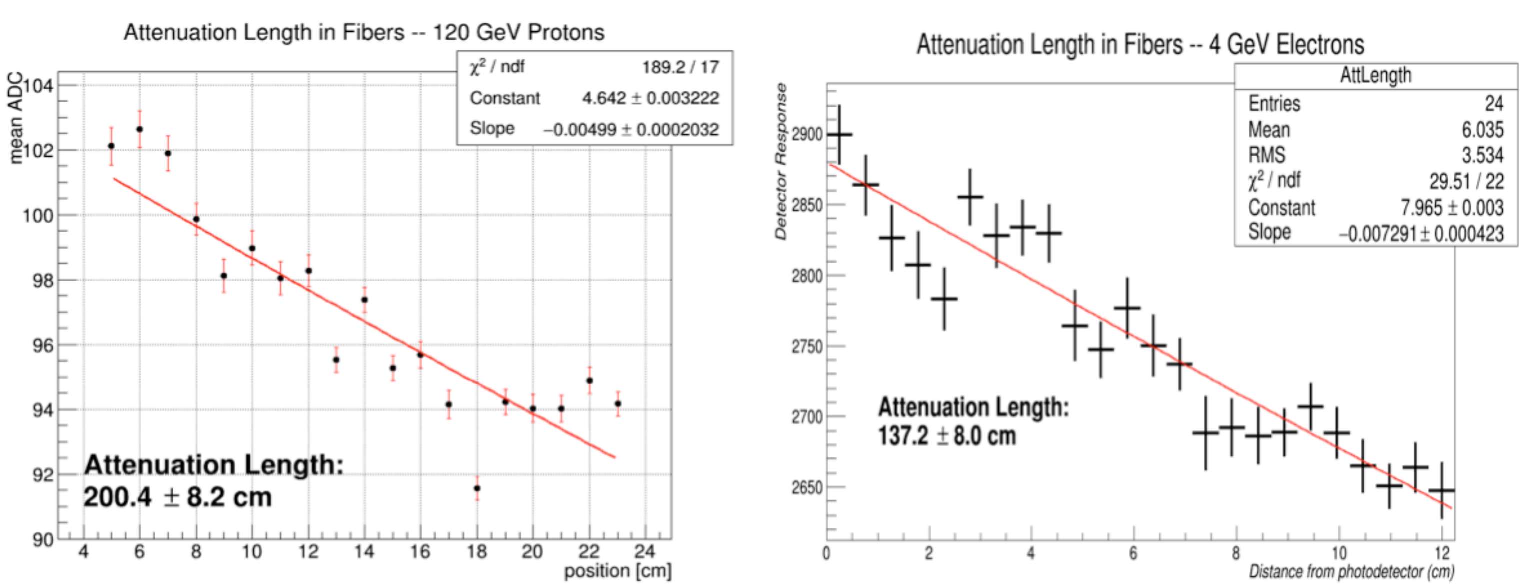


Figure 4. Attenuation length in 0.4 mm scintillation fibers measured in the test run.

Scans along the towers with 120GeV protons and 4 GeV electrons, and measurements of transverse non-uniformities in the response did not pointed to a definite problem.

Possible explanations:

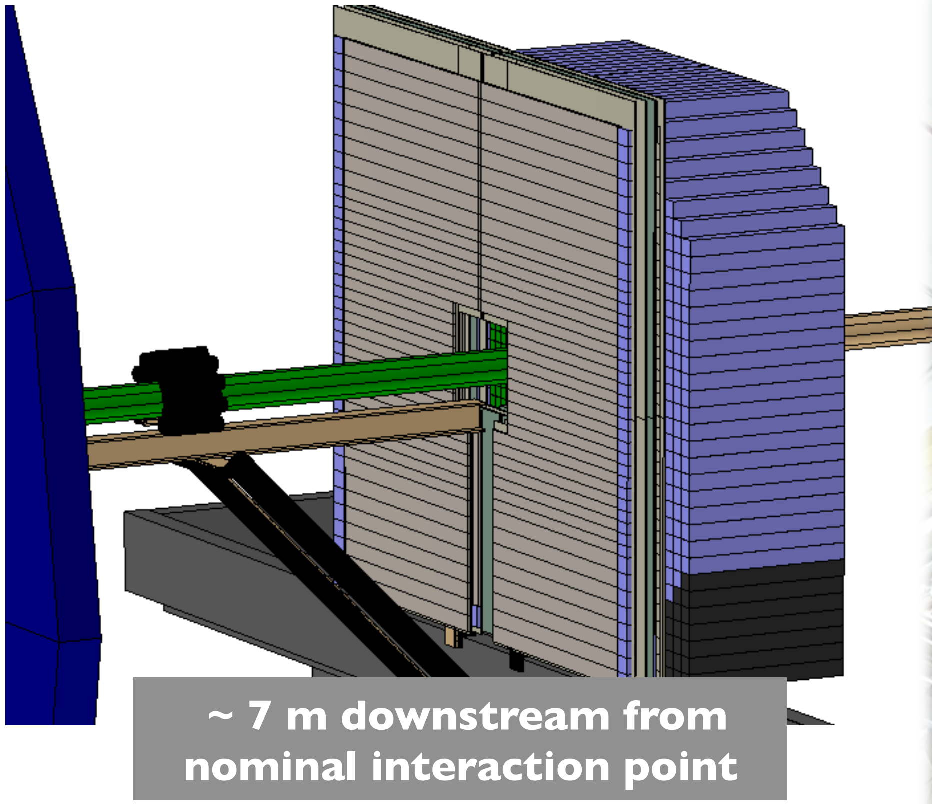
1. Damages at tips of fibers due to straight cut through Absorber/Fiber mixture (by mistake), that was not in all other prototypes.
2. Non-uniformities in composite absorber.
3. Imperfections in the filter and compact readout scheme.

- Transverse non-uniformity of response is 2.3% vs 1.4% in SPACAL tested in 2012 with PMT readout.
- Attenuation Length similar to what was measured for 0.47mm fibers in previous SPACAL. (MC 75 cm)

Looking back, mistake was made of combining few new things at once and pushing resolution down. Should have been using 2012 approach one step at a time.

SiPM Rad Damages Studies:

- **Run 15, STAR FPS (Forward Preshower Detector) first time SiPMs used for Physics Measurements at RHIC.**



- 3 Hodoscope layers, each 84 ch.
- 3mm x 3mm Hamamatsu MPPC
- 50um cells in layer 1 and 2
- 25um cells in layer 3

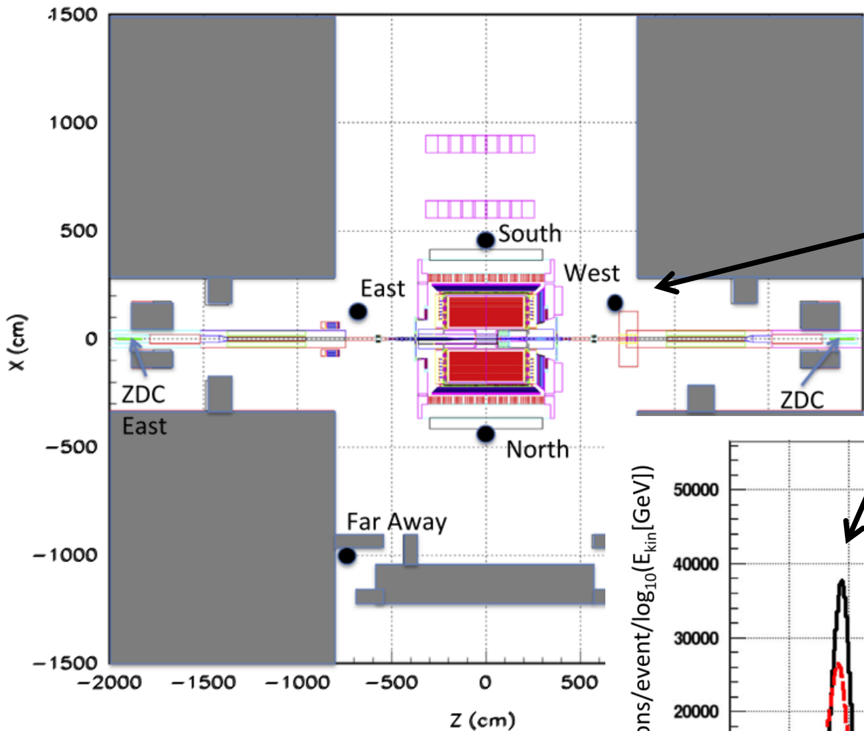
- Very successful project.
- Smooth operation from 'Physics' day one in pp, pAu, pAl.

- Operated by STAR detector ops.
- Daily pedestal runs, I/V scans.

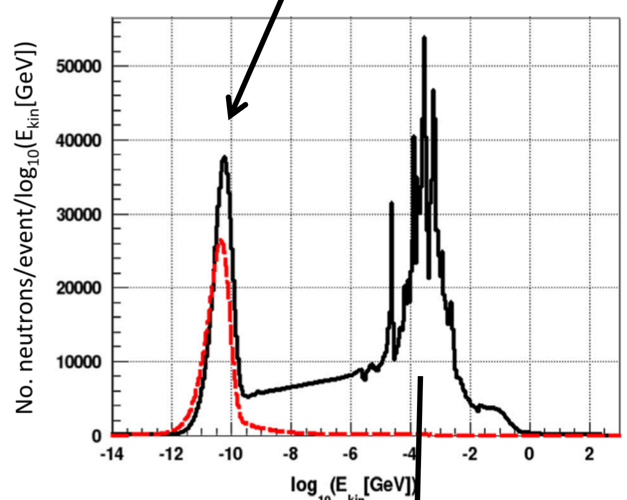
3 sets of 10 TLDs were installed around FPS/FMS (each set stayed ~4 weeks, data still under analysis).

For pAl added CERN RadMons (similar to one used at PHENIX IP)

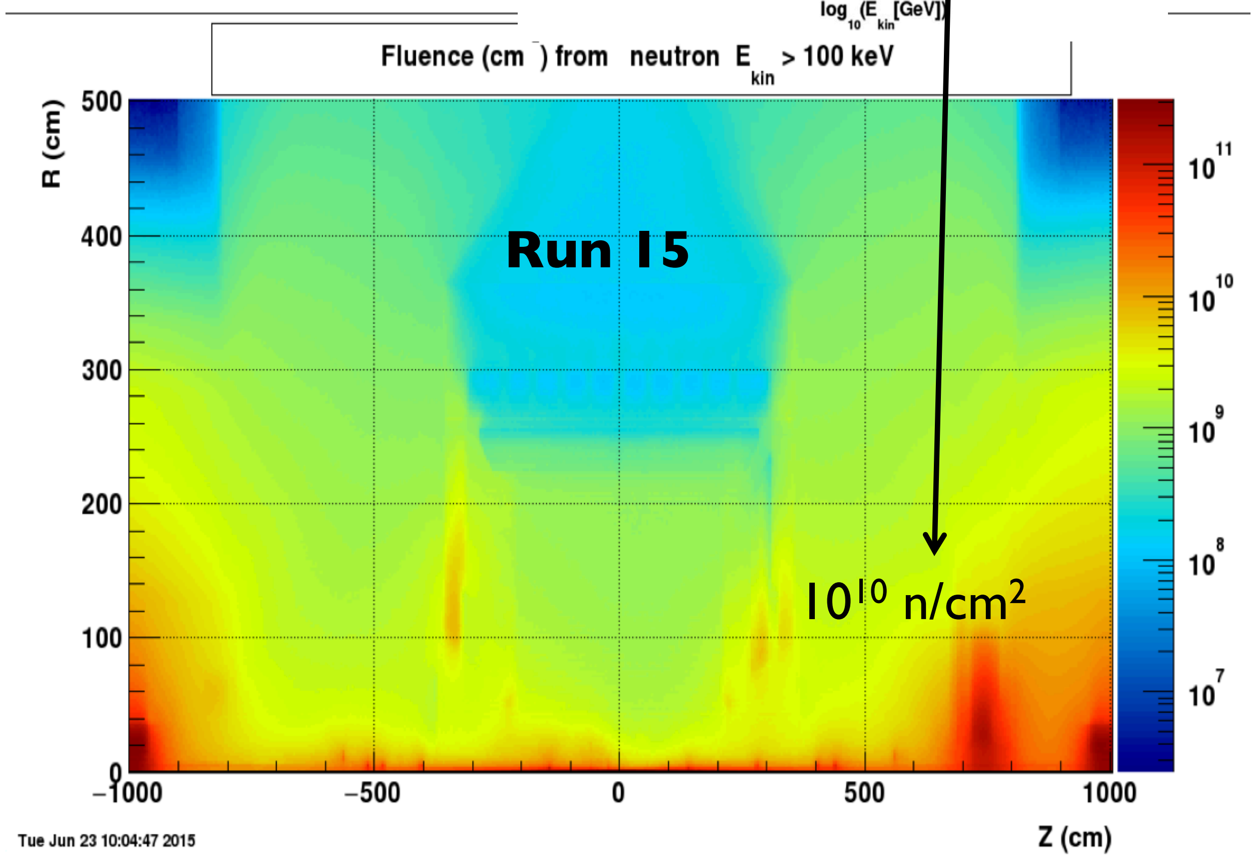
Neutron Fluxes, FPS SiPMs:



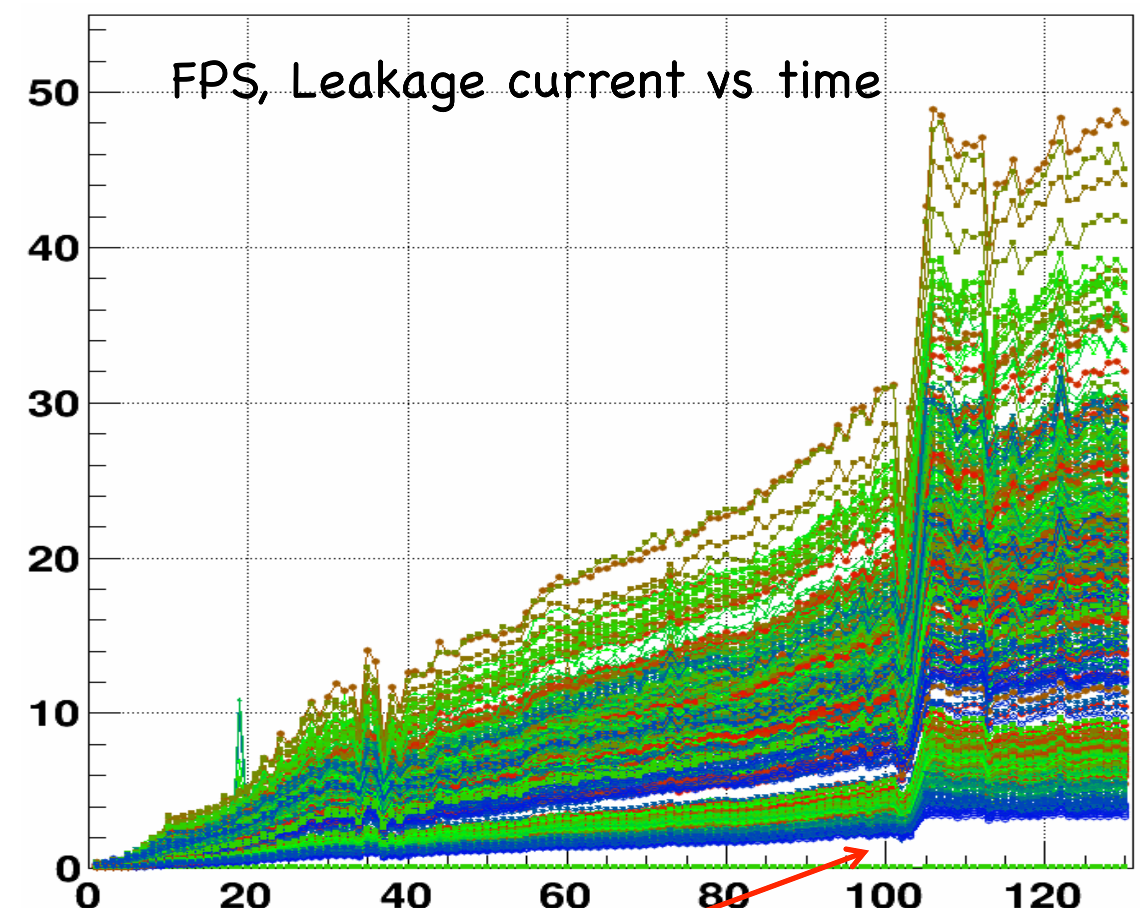
Run 13, He3 Counter. Thermal Neutrons



Y.Fisyak, et.al NIM A756



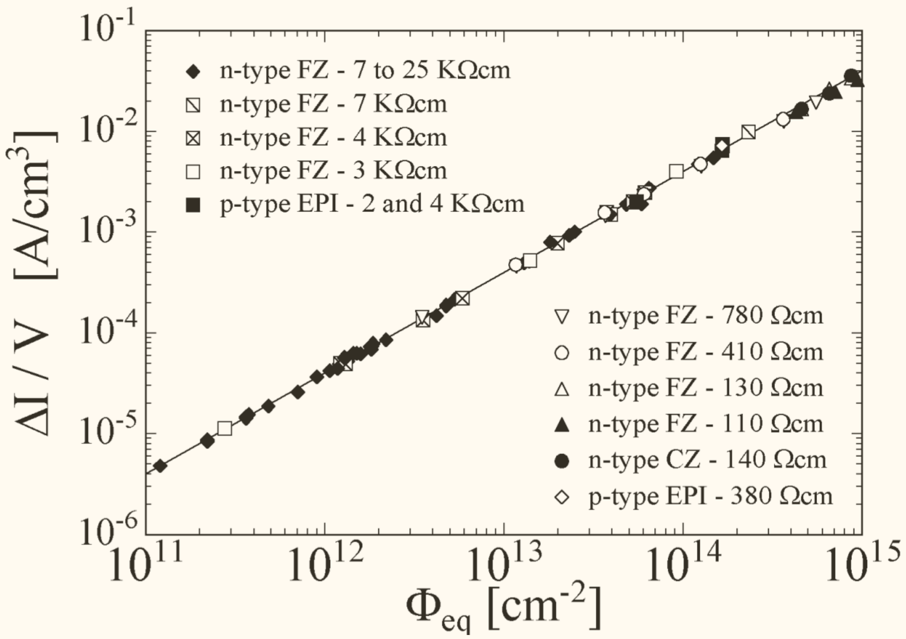
- 2015 Neutron fluencies calculated for pp, pAu, pAl for integrated delivered luminosity.
- FPS SiPMs were exposed to 10^{10} neutrons sm^{-2} according to our MC.
- MC doesn't know about beam losses, APEX or high background during steering, collimations etc., i.e. real exposure may be higher than MC gives.
- Data from TLDs still in processing.

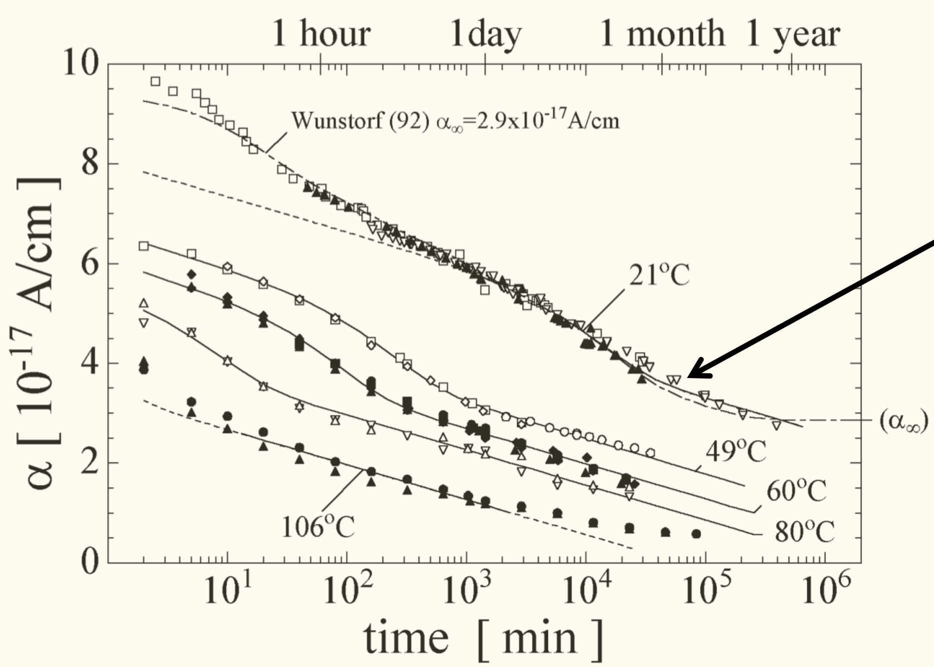


May3rd when beam blasted in WAH
~5weeks pp running worth of rad damage in 1 day

SiPM Leakage Current vs neutron fluence expected vs measured at RHIC Run15 (STAR and PHENIX IR)

$$\Delta I = \alpha \, \Phi_{eq} \, V$$

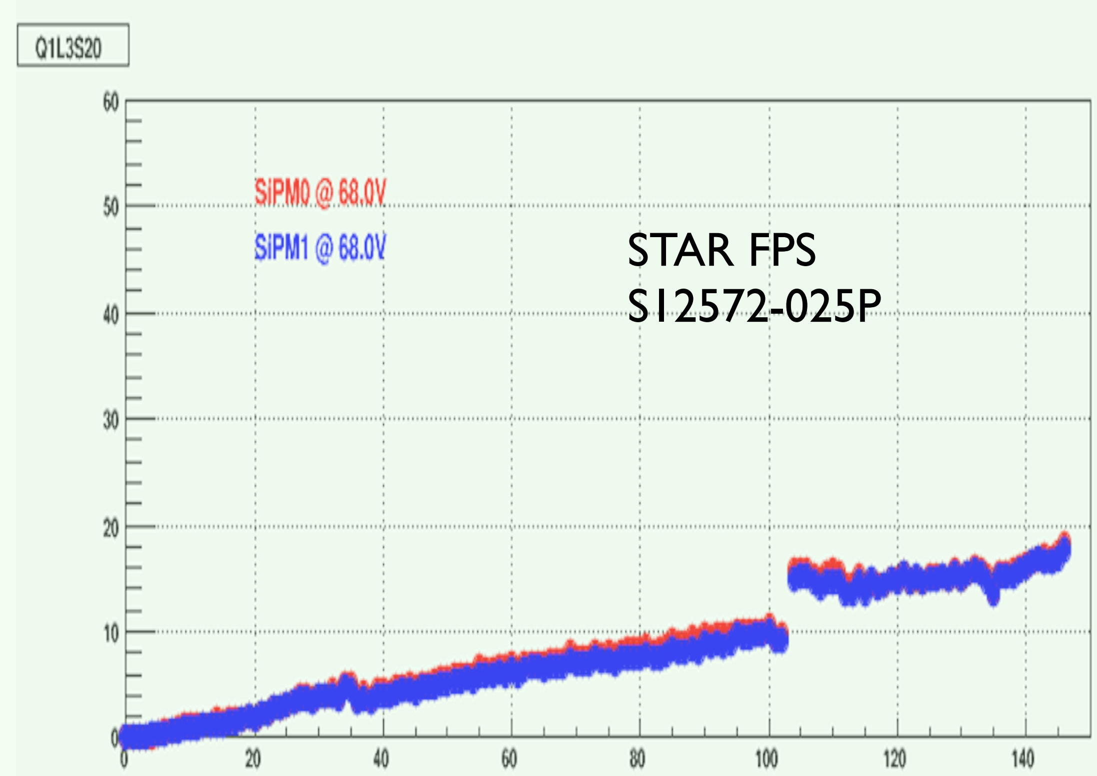




M. Moll Phd.Th.

For SiPMs effect is the same as in normal junctions:

- Independent of the substrate type
- Dependent on particle type and energy (NIEL)
- Proportional to fluence



- STAR FPS alpha = 3.5 * 10^{-17} A/cm
- Thickness of depleted region ~5 um, Gain $5*10^5$
- At 10^{10} n/cm^2 I = 9 uA, Measured 10 uA

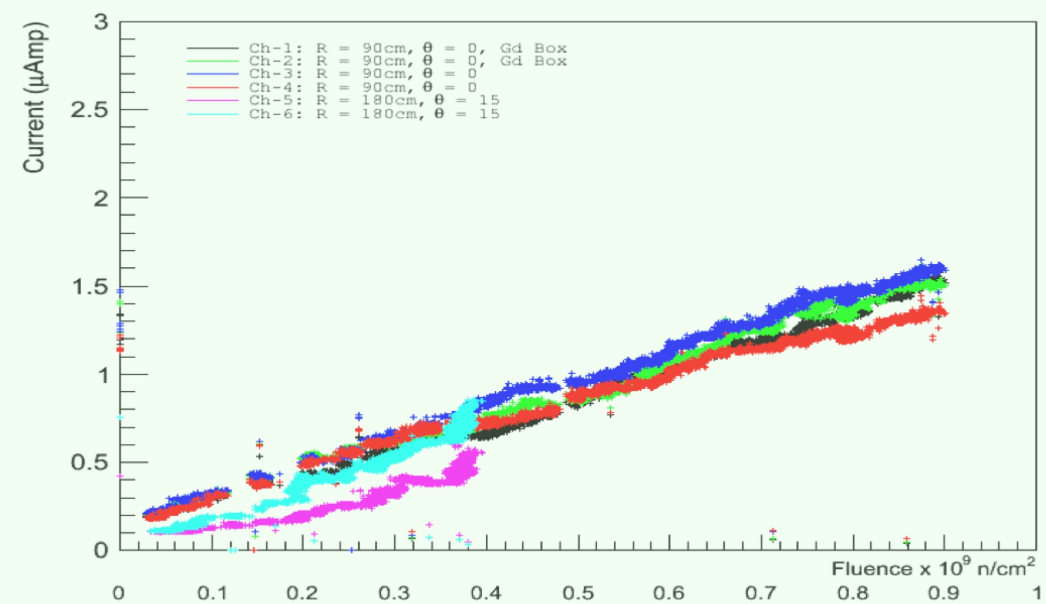
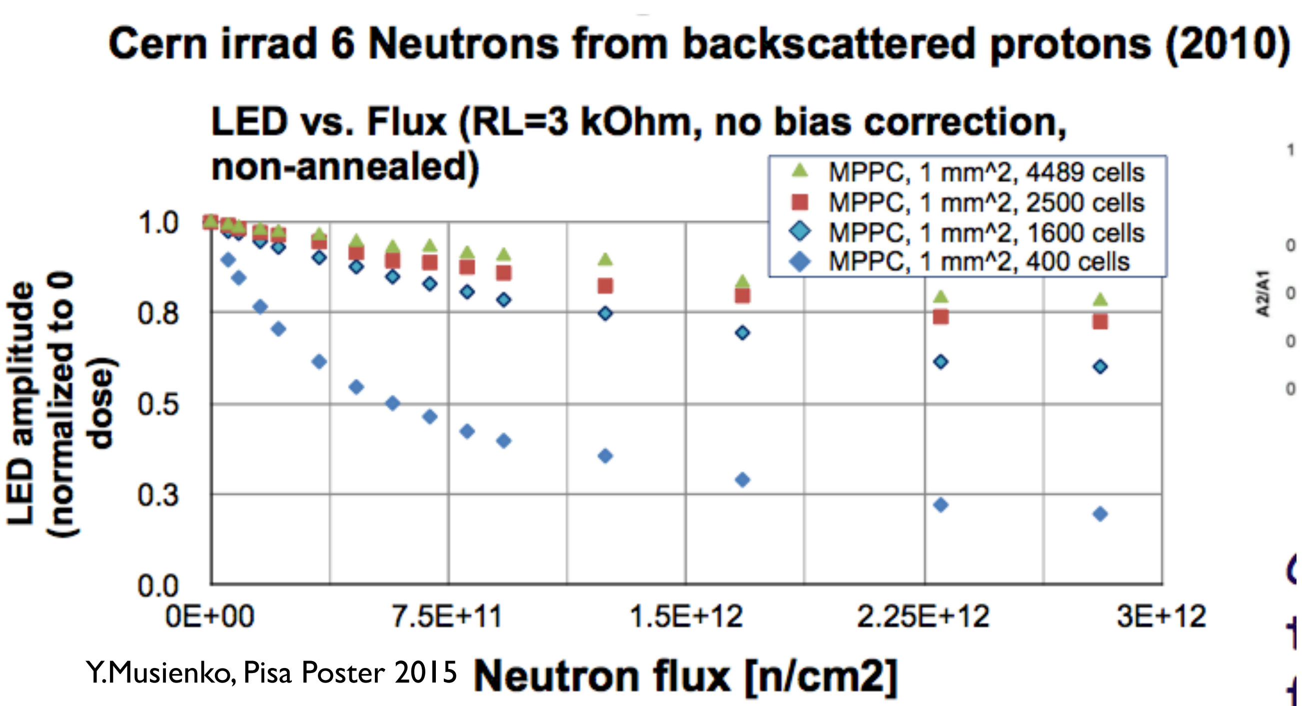
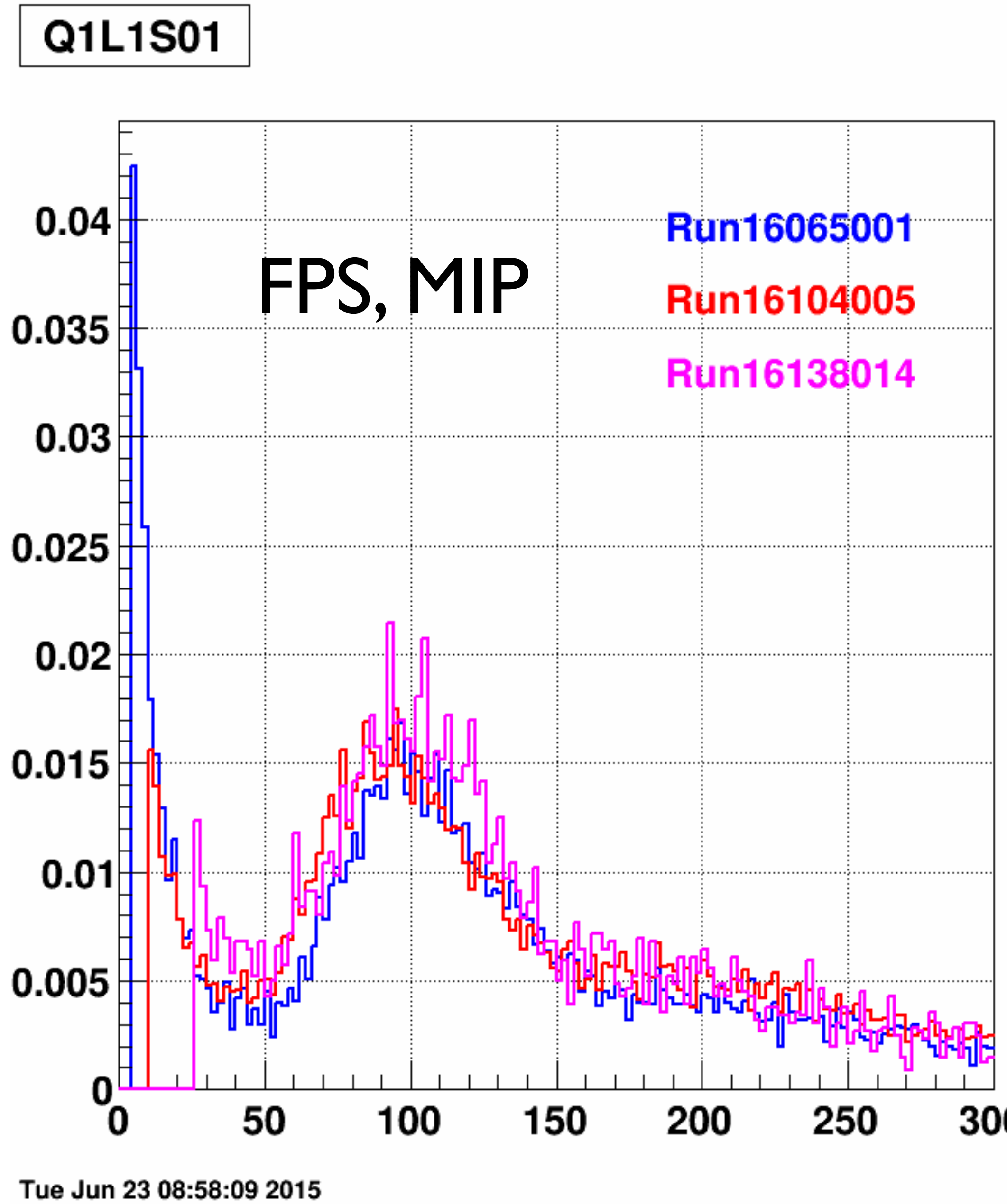


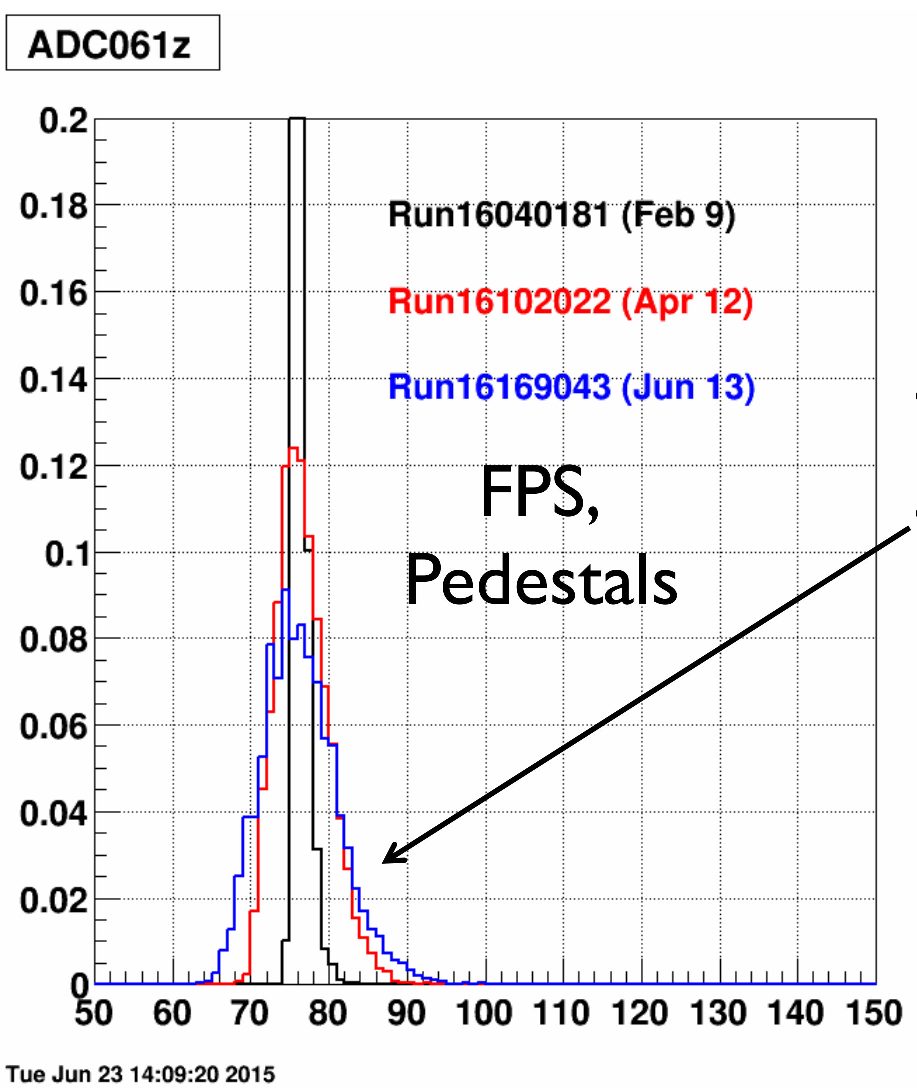
Fig. 8. Hamamatsu S12572-015P SiPMs placed in the PHENIX IR during the current RHIC run. Channels 1&2 were enclosed in a Gd box that absorbed all thermal neutrons. Channels 3&4 were unshielded in the same location. Channels 5&6 were also unshielded and located at the base of the central magnet next to a SPACAL block.

SiPM 'Gain' Stability, Noise :



Y.Musienko, Pisa Poster 2015



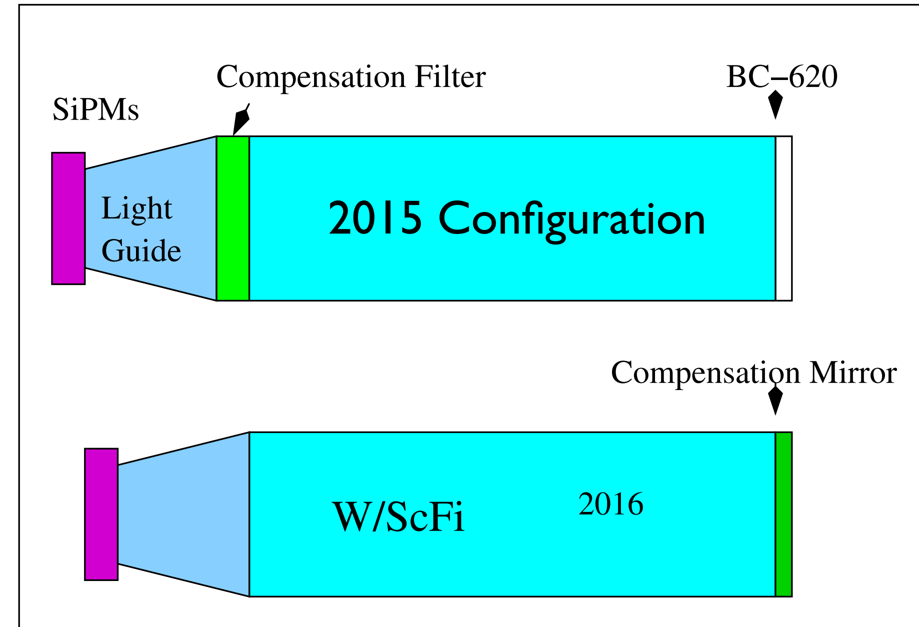


- Two 3x3 mm2 Hamamtsu S12572-025P SiPMs per channel.
- Noise ~ 5 p.e. in ~65 ns integration window. Increased 5 times.
- Verified predictable changes in SiPM characteristics under irradiation in real experimental environment.
- Even more confident in MC modeling of neutron fluxes.

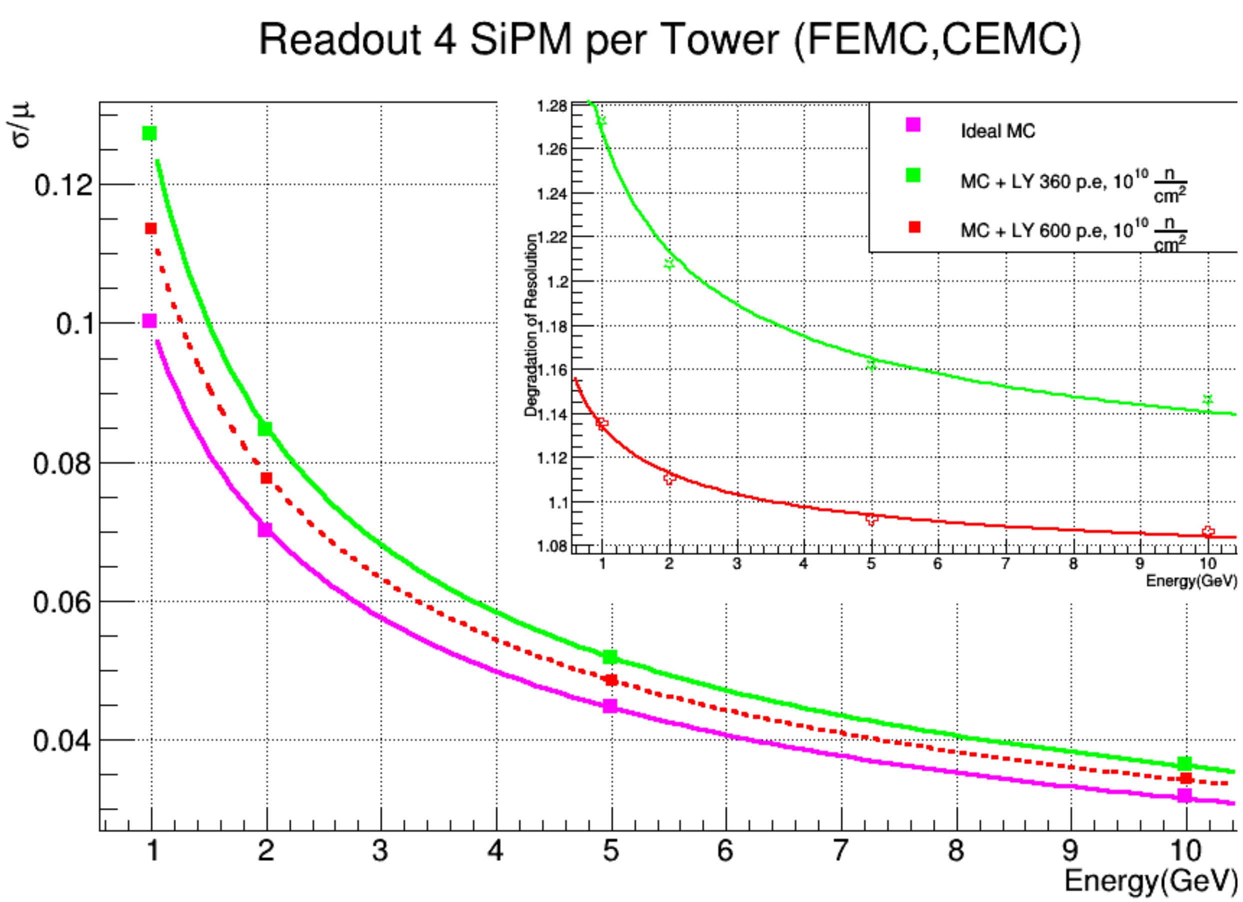
Projected calorimeters performances:

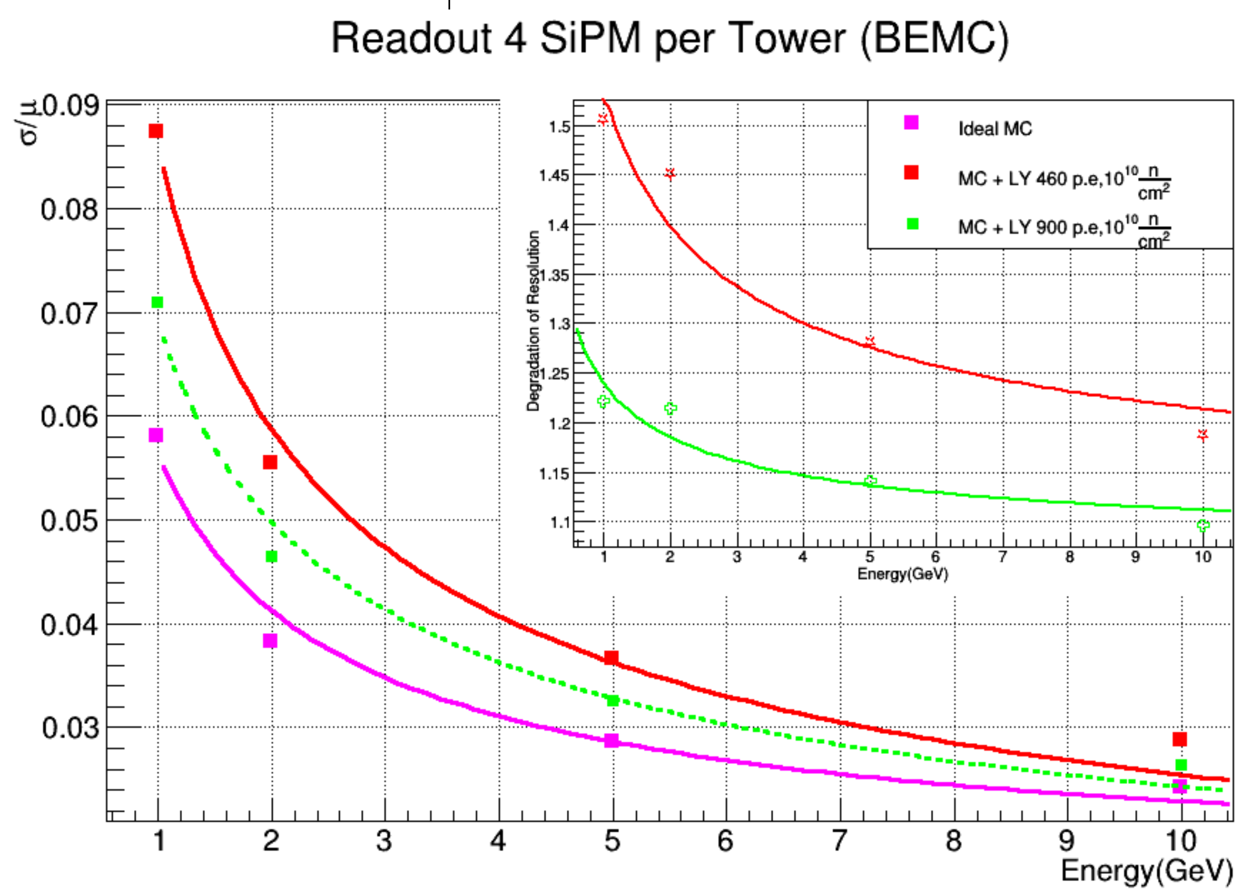
- Cluster 3 x 3 towers, 4 SiPMs per tower. Noise after 10^{10} n/cm^2 ~ 21 p.e.
- FEMC, CEMC - Light Yield in hand ~ 360 p.e. (2015 test run)
- FEMC, CEMC - Light Yiled possible ~ 600 p.e. (better PDE on new sensors, refined light collection scheme)

- Compensation in light collection scheme should be made on the back side to improve light yield.



Proposed change in light collection scheme.





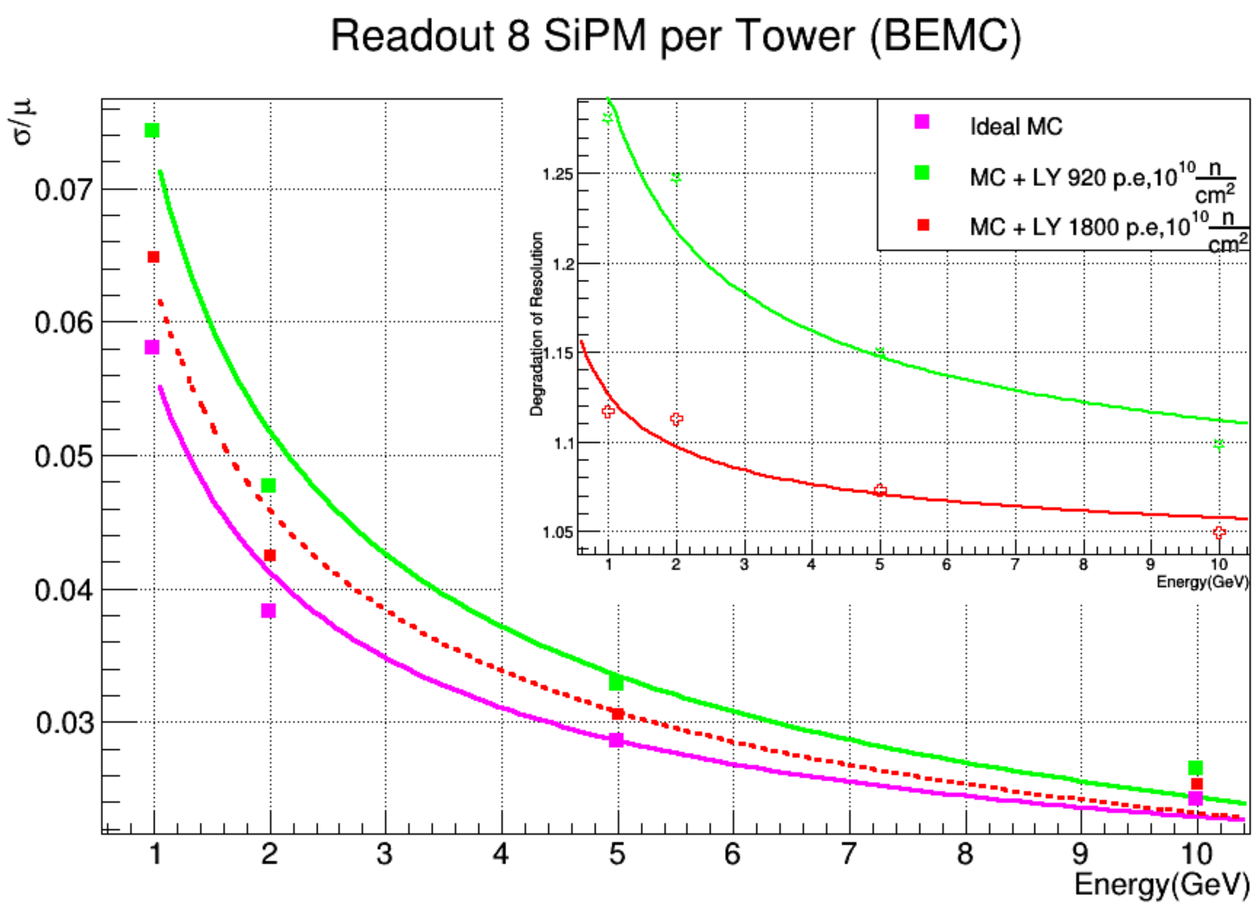
BEMC – Light Yiled possible ~ 900 p.e. (better PDE on new sensors, refined light collection scheme), which is not enough.

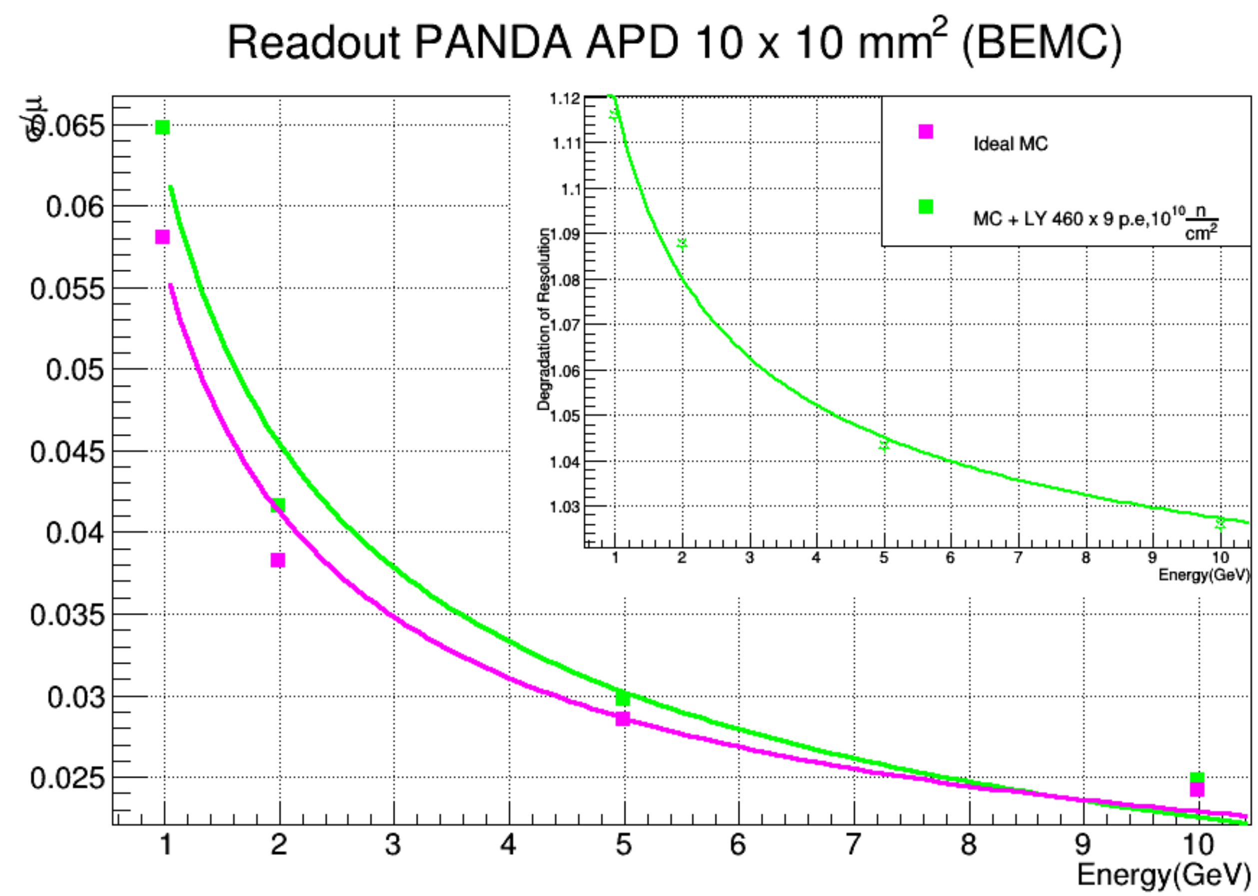
- Right now we are still very puzzled with 460 p.e. (BEMC) measured in test run 2015.
- Concern about thin Sc. Fibers is growing.

Possible schemes of improvements for 'HR' BEMC:

- Cluster 3 x 3 towers, 8 SiPMs per tower.
- Noise after 10^{10} n/cm^2 ~ 30 p.e.
- BEMC - Light Yield assumed ~ 460 p.e. x 2
- BEMC - Light Yiled assumed possible ~ 900 p.e. x 2

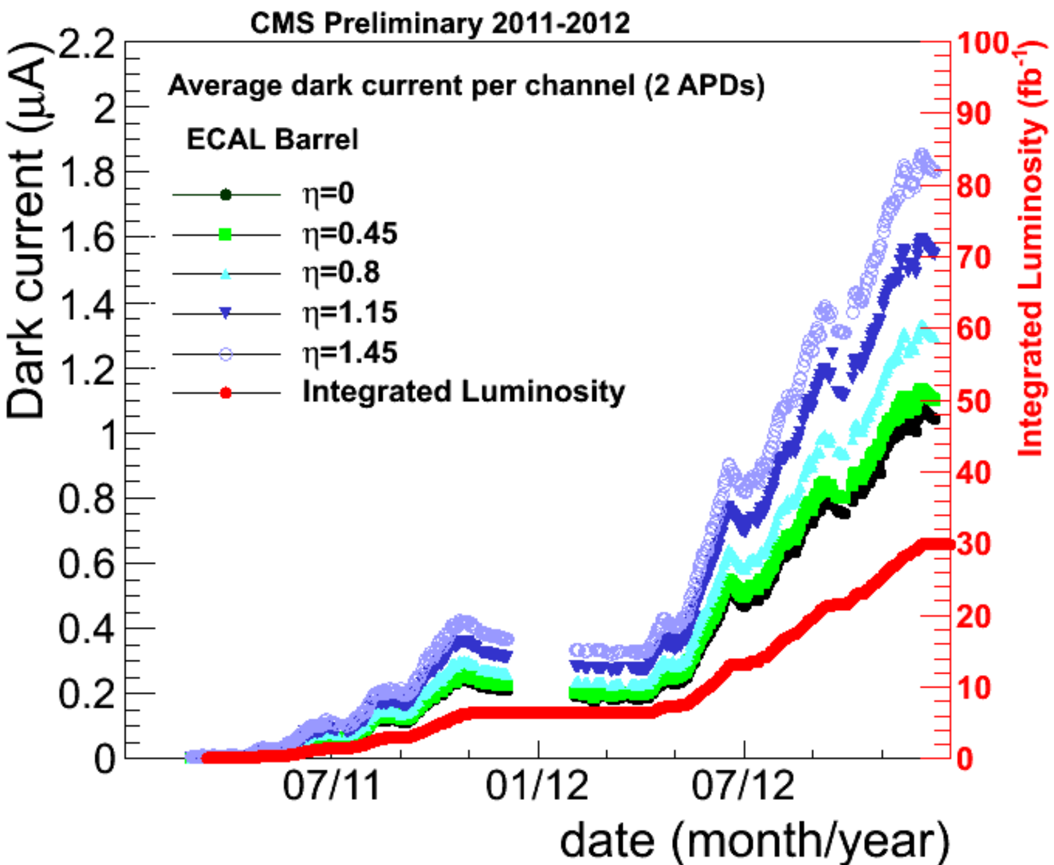
- BEMC – Light Yiled assumed ~ 460 p.e. x 9 (9 - PDE x Area of APD compare to 4 SiPMs)
- ENF – 1.4 (PANDA TDR).
- Preamp ENC – 50 p.e. (270 pF) before amplification 50 (state of the art preamp, discussed with G. Visser (IUCF))

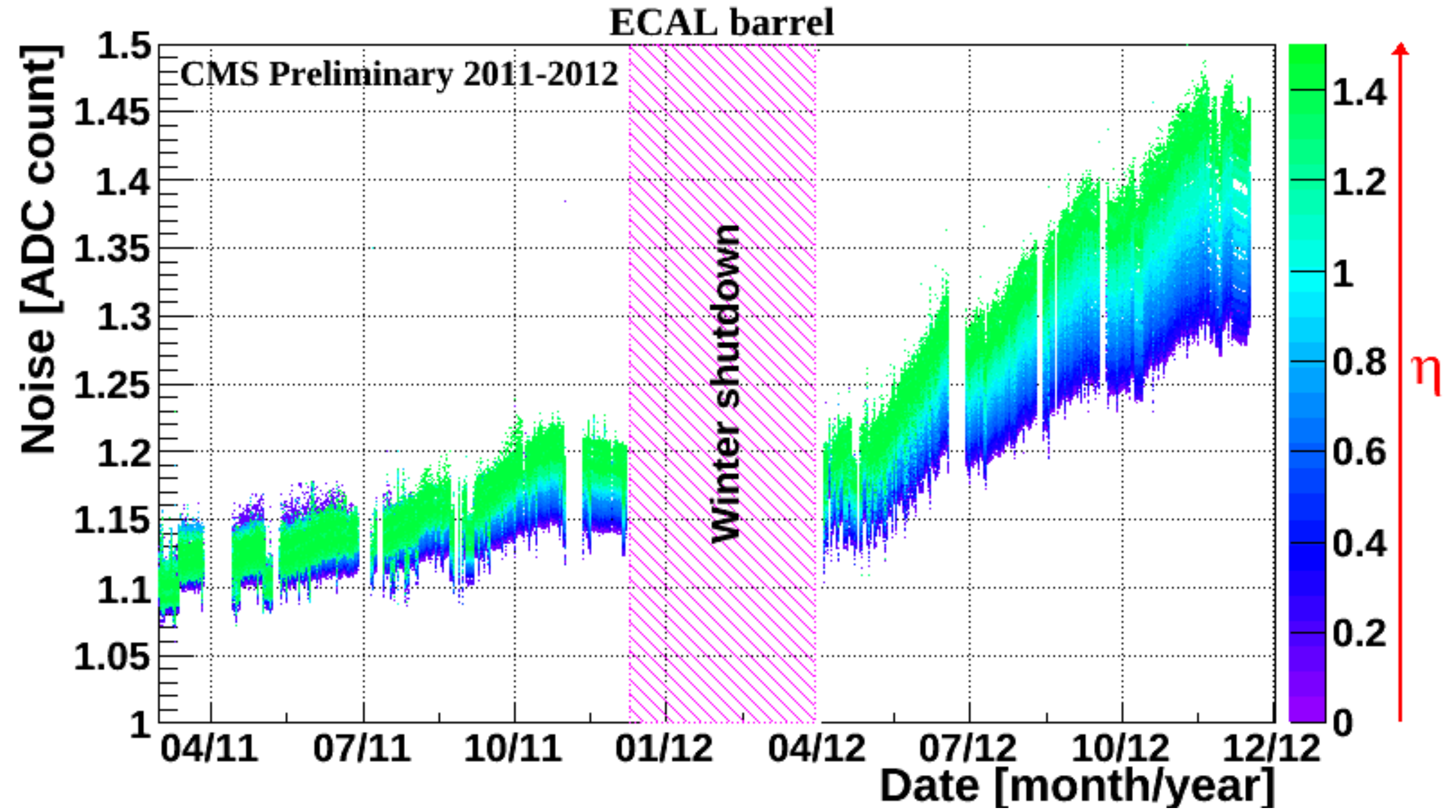




- In 2016 we will not try any of these schemes for BEMC.
- First we need to understand what is intrinsic energy resolution of BEMC W/ScFi configurations.

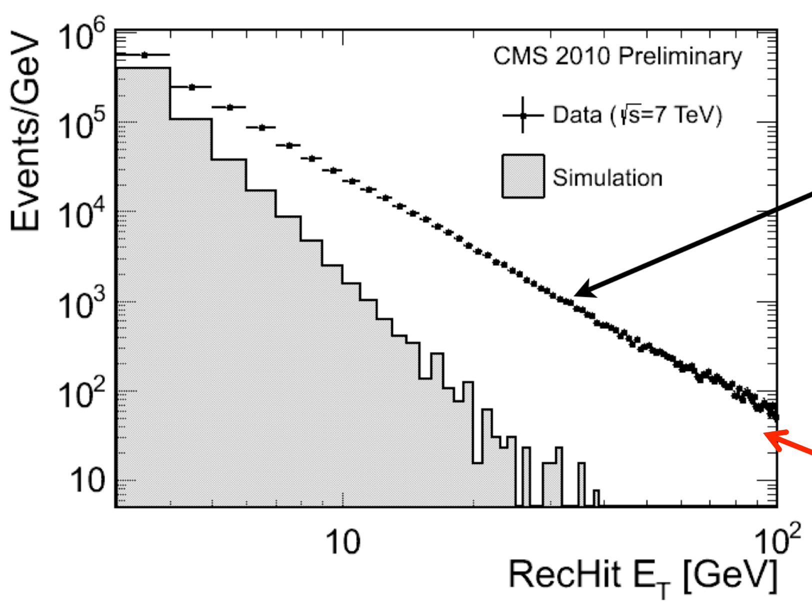
Good and bad things about APDs:





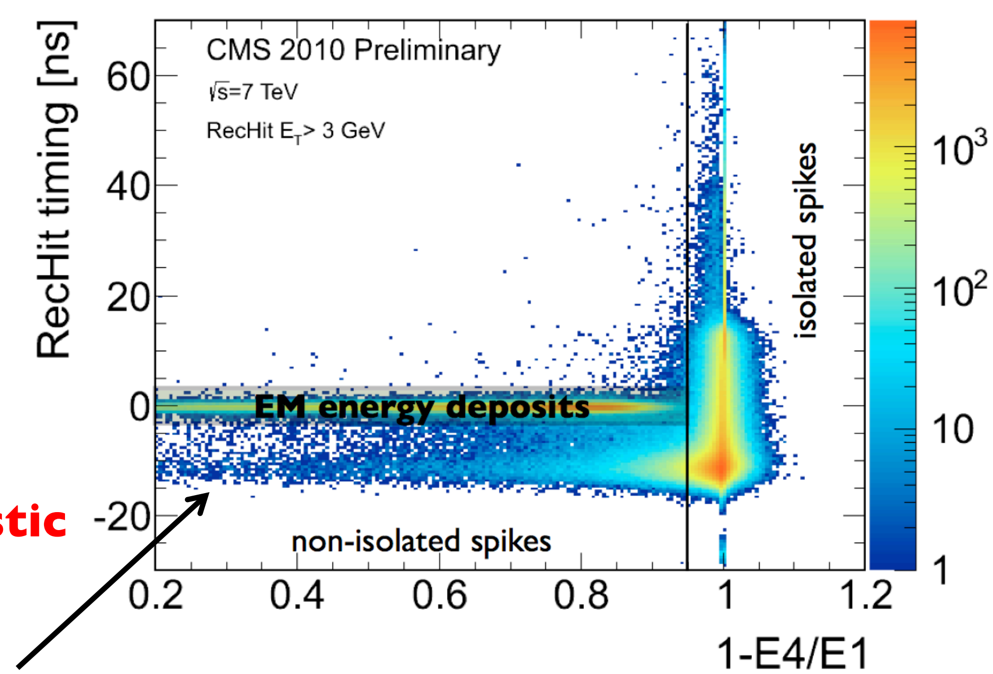
CMS, 50 fb^{-1} -> $2*10^{12}$ n/cm^2

Noise increase from 43 MeV to 55 MeV



Significant excess of high energy signals due to spikes
(spikes not included in the MC shown here)

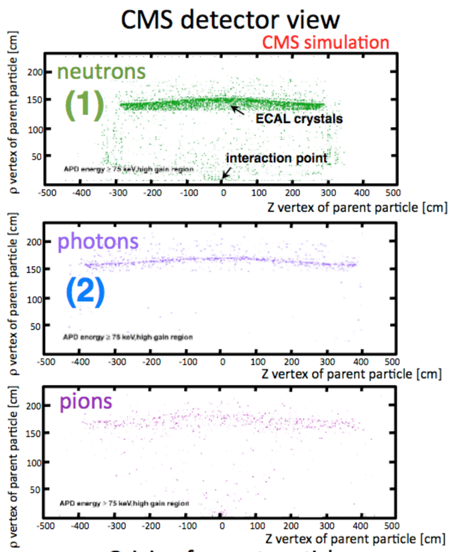
This is why it is good to test systems in realistic environment.



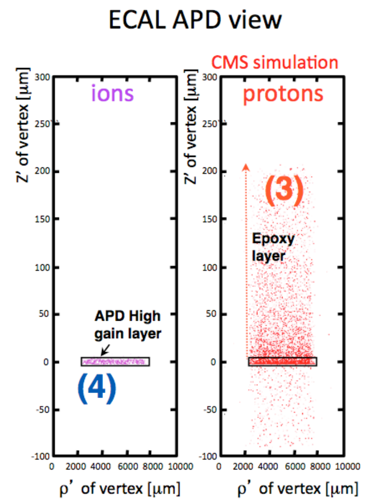
- Reason to use 3HF (green) fibers, slow ~ 7 ns decay time (PWO) + radiation hard + better match to APDs QE.
- But, there were reports that LY is ~50% of SCSF78

Are SiPMs immune to anomalous signals?

"Yes" <- widely believed, as it was with thin APDs before CMS seen first collisions.



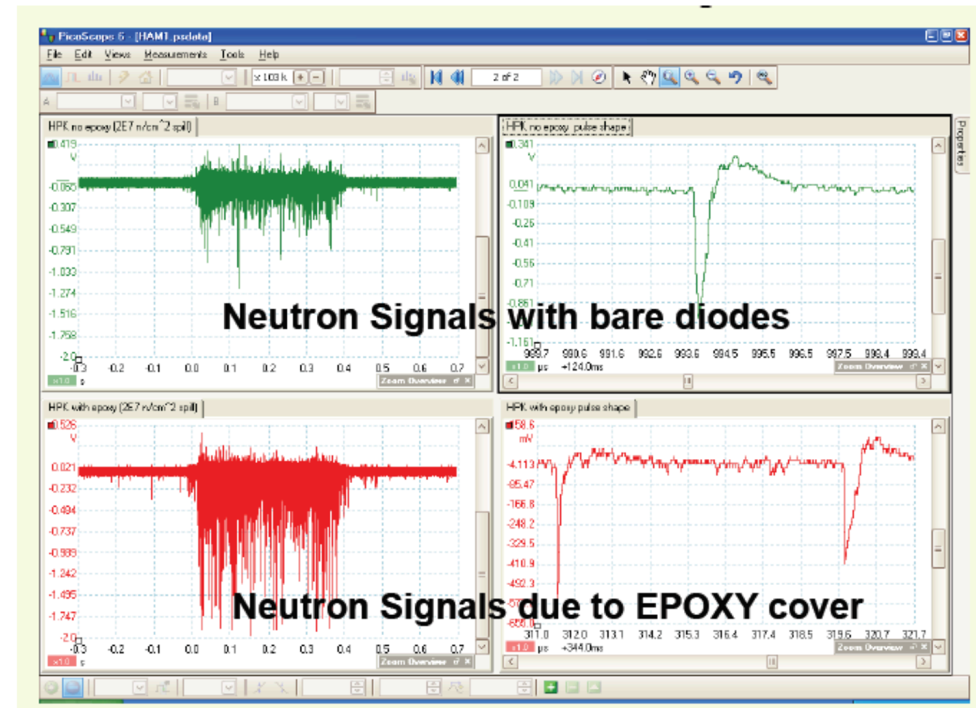
Origin of parent particle
z - distance along beam axis
ρ - distance perpendicular to beam axis



Origin of particle hitting APD
ρ' - distance along APD
z' - distance perpendicular to APD axis

- (1) neutrons produced in the ECAL crystals
- (2) photons produced close to the APD layer
- (3) anomalous signals produced by np scattering in the protective epoxy coating of the APD.
- (4) Ions (silicon nuclei) directly ionize the APD active volume.

Neutron signals in Hamamtsu MPPCs

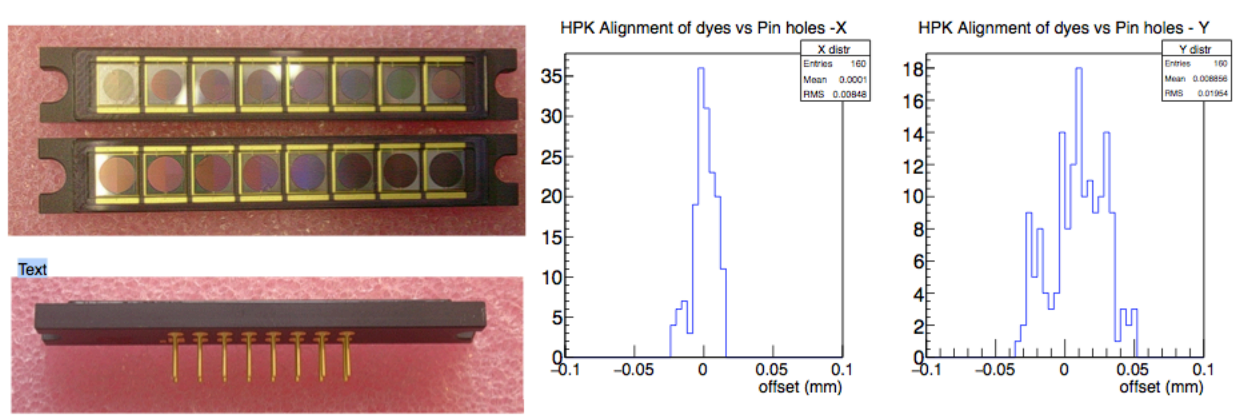


Signals from Bulk? We will try Boron-11 and thinner diode

: on March, Protvino, 16.11.2011 Y. Musienko (Iouri.Musienko@cern.ch) 60

Custom packaged Arrays

With 0.3 mm glass window



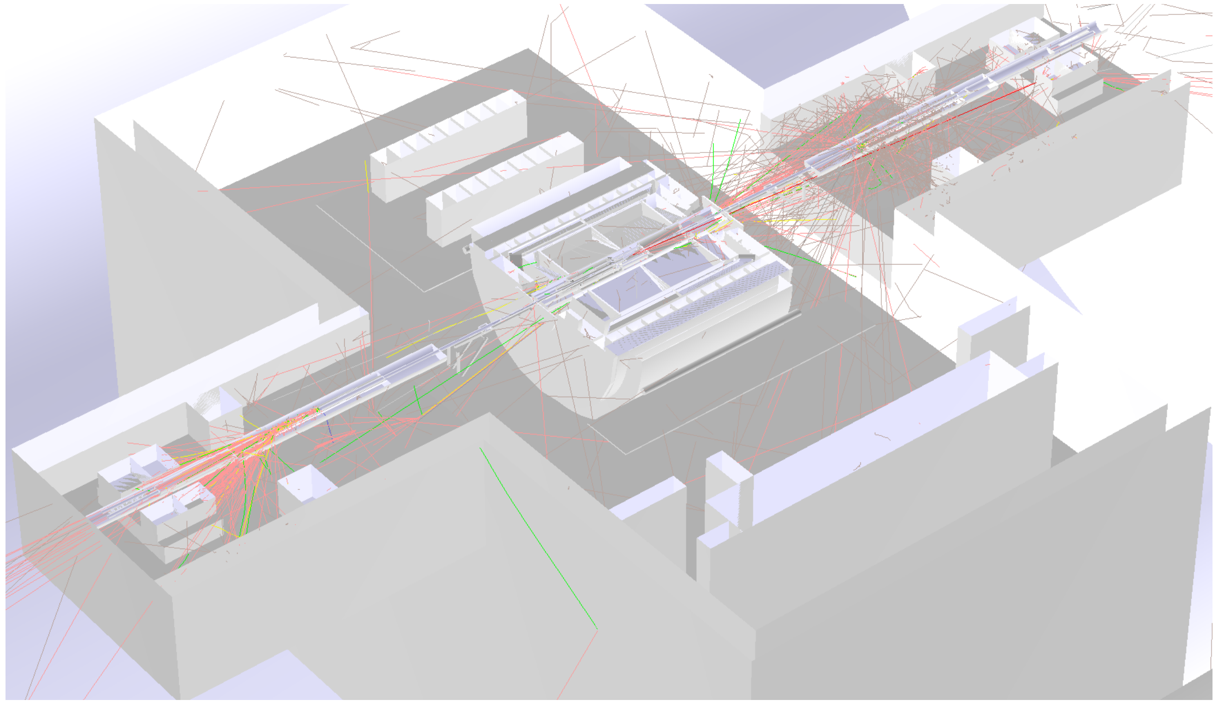
R&D on large dynamic range SiPMs in collaboration with Hamamatsu started in 2010. We now have 15 micron cell devices in 2 sizes, 2.8 mm and 3.3 mm diameter with reps. 27500 and 38500 cells. The 2.8 mm can readout a sum of 4 fibers and the 3.3 mm can readout a sum of 7 fibers

- CMS upgrading HCAL with SiPMs (fluencies up to 10^{12} n/cm^2)
- Epoxy protection window creates problems in both APDs and SiPMs
- Seemingly, mechanism is different (np scattering in APDs) vs some sort of scintillation for SiPMs.

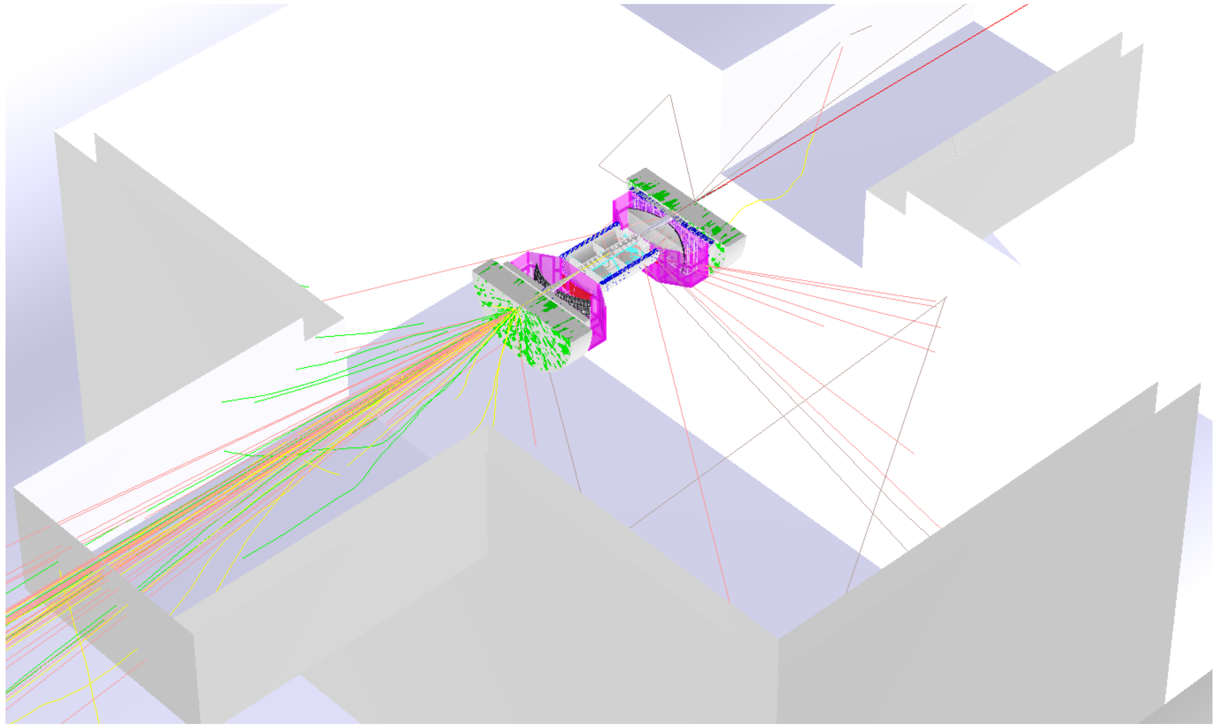
Should we worry about this at EIC environment?

Neutron flux estimation in EicRoot

STAR geometry imported in EicRoot

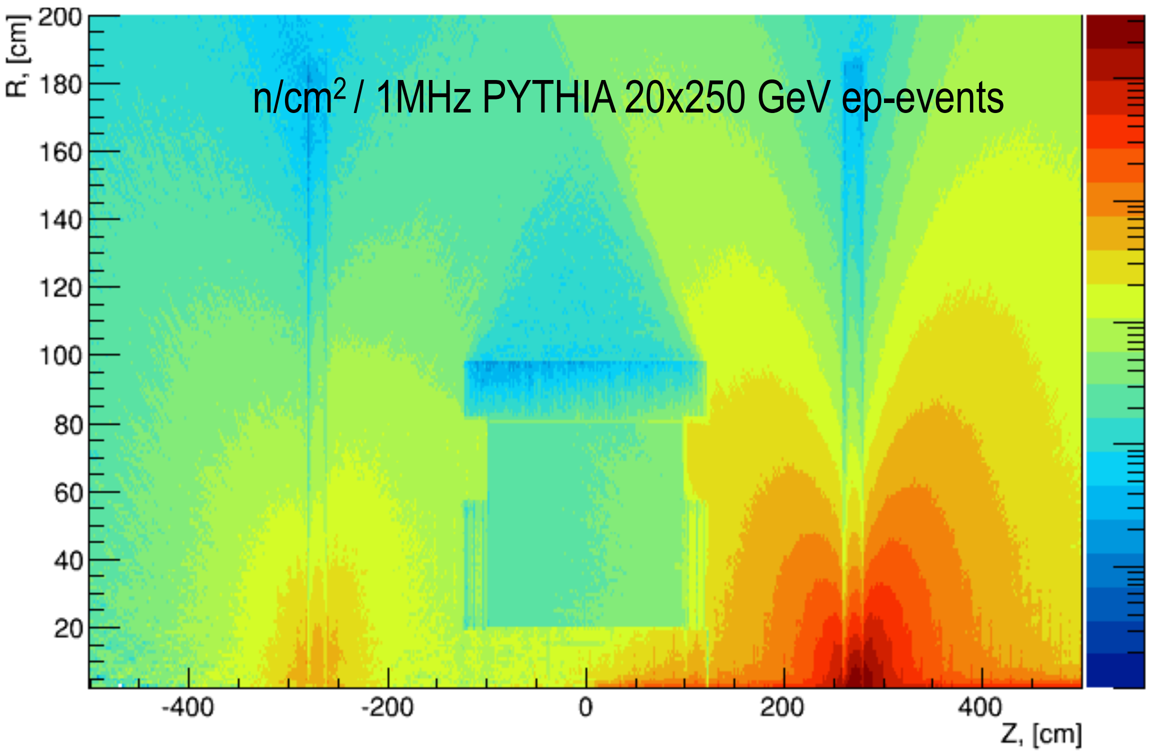


BeAST detector placed in STAR hall



Strategy:

- Import STAR geometry (including experimental hall)
- Run ep- and pp-PYTHIA simulations for STAR and BeAST setups
- Use direct STAR neutron flux measurements from 2013 as a reference



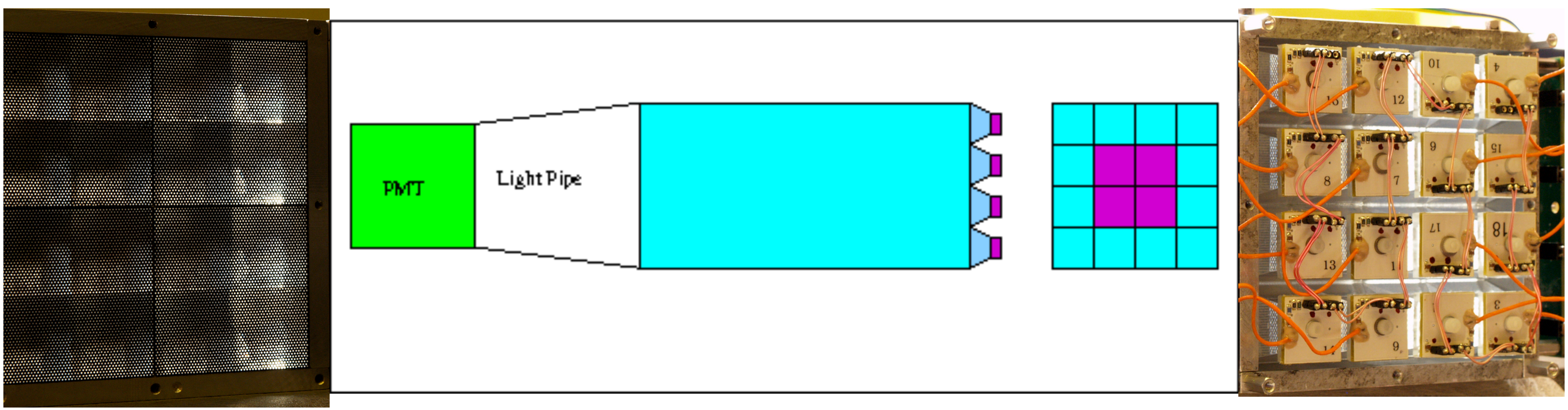
Expected neutron flux in BeAST (preliminary)

work has just started …

A. Kiselev (BNL)

Can we quantify anomalous signal rates using RHIC?

- Equip FEMC prototype with a single PMT readout from the back side + monitoring system.
- Place at STAR IP in forward region with known (MC) and monitored RadMons, (SiPMs itself) neutron background for Run 16.
- Arrange HT trigger from four central towers readout by silicon sensors.
- Correlate with PMT signals.
- Ideally want to have both FEMC prototypes readout by APDs and SiPMs at the same time in the same location.
- Timing information probably out of reach for Run16, look only at 'swiss cross' if any abnormal signals observed.
- If need use IUCF LENS to look at direct signals from sensors (1 us beam pulse, 10 Hz).



Plan for sampling calorimeters FY16:

- BEMC, CEMC, FEMC - Boost LY with compensation from the back side.
- BEMC existing prototype re-work at UIUC, prepare for single PMT readout.
- BEMC build new device with thicker fibers, single W absorber, optimized with MC, i.e. goal to have as minimal as possible uncertainties for simple test run data interpretation.
- BEMCs test at FNAL, determine limit on intrinsic resolution, make decision if this technology is right for 'HR' type.
- FEMC build detector with 3HF fibers, optimized for APDs (rad hardness next to the beam pipe, i.e. similar to PWO at back side, possible option for 'HR' readout).
- Quantify rate of anomalous signals for SiPM and APD based readout.

Future planning (~2018). Sampling calorimeters

Utilize unique opportunity to test complete EMCal system at RHIC (STAR IP) before EIC will start. Need large scale EM+HAD (Forward system as easiest). Use it as a platform for future developments/tests FEEs, DAQ, Monitoring, Slow Control components in 'realistic' experimental environment (discussions about some of these component in progress, but no proposal yet).

Future Plans (BNL PHENIX Group)

- Continue to develop the procedure to build fully projective spacal modules using similar techniques that were used to produce single projective modules. This will be done primarily at BNL and UIUC and will be funded by sPHENIX R&D funds.

- Continue to develop procedures for mass production of spacal modules using the standard 1D projective design. This will be done primarily at THP, but improvements to the process will also be developed at UCLA, BNL and UIUC.

- Construct an 8x8 prototype calorimeter using single tapered modules produced at THP using their mass production method. This prototype will then be tested as part of a beam test of the sPHENIX calorimeter systems at Fermilab in the spring of 2016.

- In parallel, we plan to transfer the technology for producing double tapered modules to THP and adapt this procedure to their mass production process. We will then ask them to produce a second 8x8 array of modules that will be used to construct a second prototype that will be tested at Fermilab later in 2016.

- Carry out additional tests of SiPMs with MeV equivalent neutrons to study the increase in dark current with dose and determine if there is any effect on the PDE at higher doses

- Develop the electronics and control procedures to stabilize the gain of the SiPMs with temperature and with increasing dark current due to radiation exposure. This will involve studies of both electronic control systems as well as cooling and temperature control.

Crystal Calorimeter R&D for the Electron-Ion Collider (EIC)

Marco Carmignotto, Gabriel Charles, Tanja Horn, Giulia Hull, Carlos Munoz-Camacho, Arthur Mkrtchyan, Hamlet Mkrtchyan, Indra Sapkota, Sean Stoll, Craig Woody, Renyuan Zhu

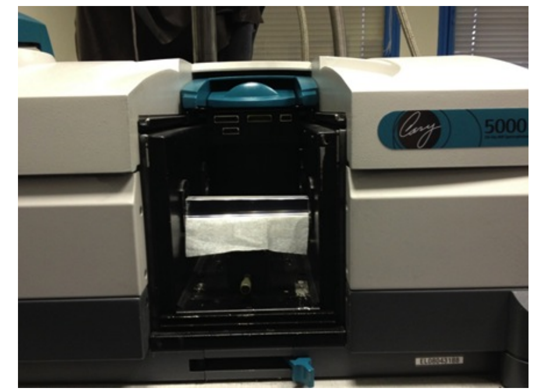
The Catholic University of America
IPN Institut de Physique Nucléaire Orsay
YerPhI
Brookhaven National Laboratory
California Institute of Technology
Jefferson Lab

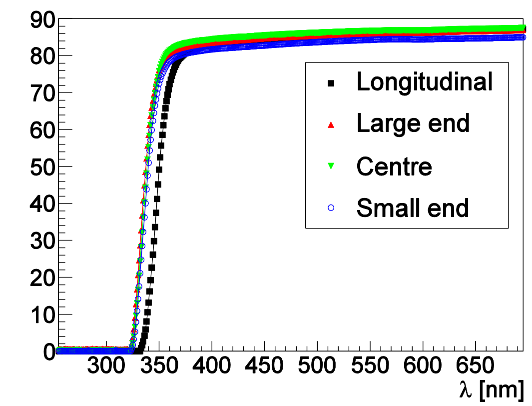
Setting up infrastructure for crystal testing at universities

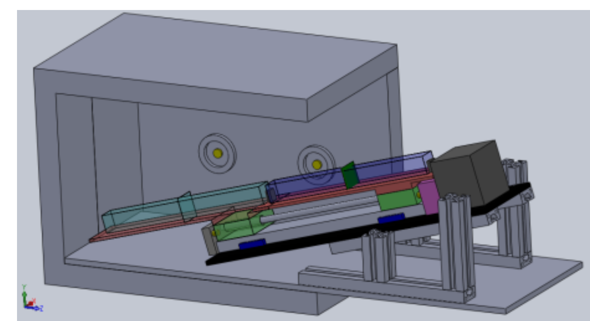
IPN-Orsay group: Gabriel Charles, Giulia Hull, Carlos Munoz-Camacho
CUA group: Marco Carmignotto, Arthur Mkrtchyan, Tanja Horn

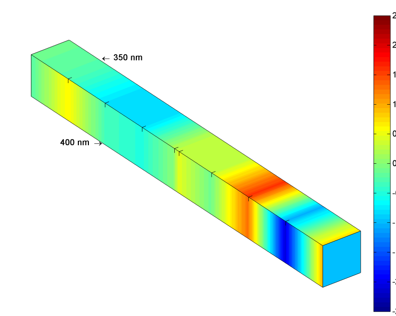
❑ Optical Transmittance

- ➢ Varian Cary 5000 (IPNO)and Perkin Elmer Lambda 750 spectrometers (CUA)
  - ○ Measures absorption along and across the crystal with 1 nm wavelength resolution between 200 and 800 nm
- ➢ Setup was commissioned with BTCP crystals on loan from University of Giessen
- ➢ To accommodate 20-cm or longer crystals more versatile configurations were designed and are being built





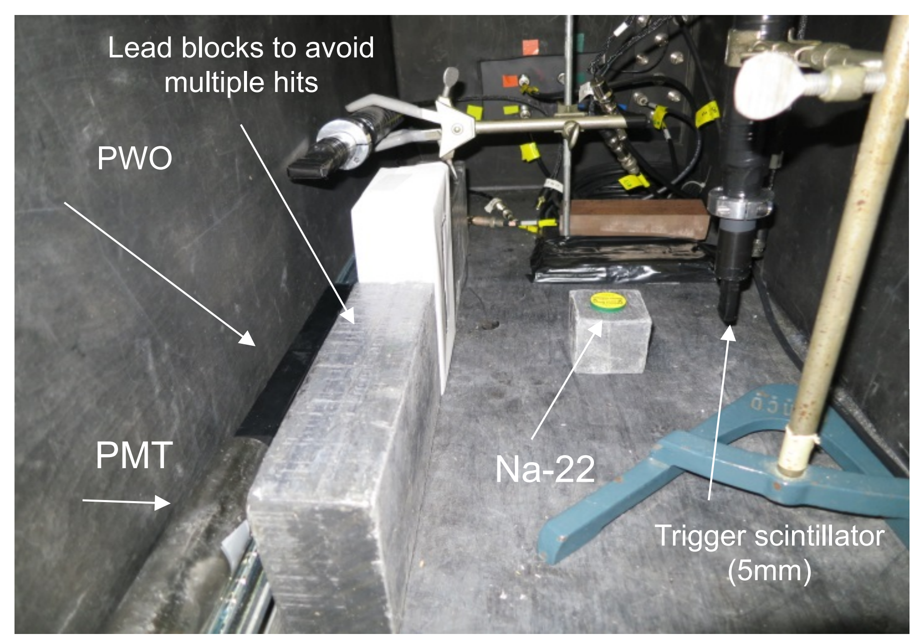


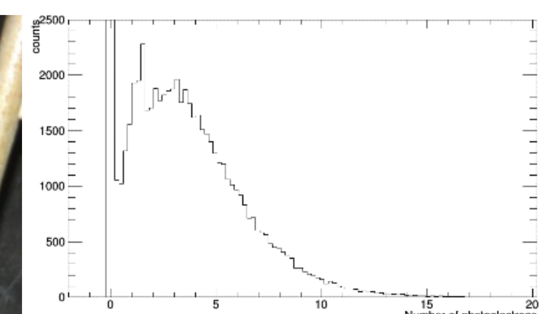


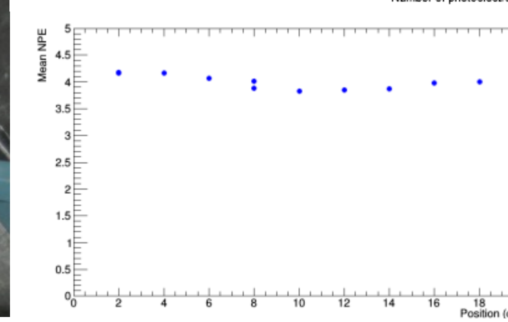
❑ Crystal light yield

- ➢ A setup is currently being built with a source and calibrated PMT
- ➢ Temperature-control of the setup is being explored

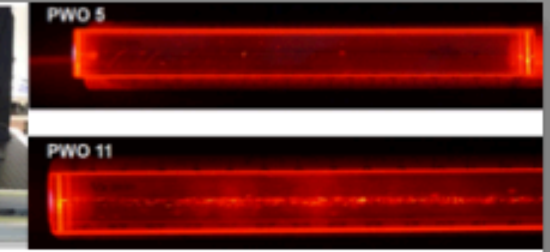
❑ Options for irradiation at the universities are being explored



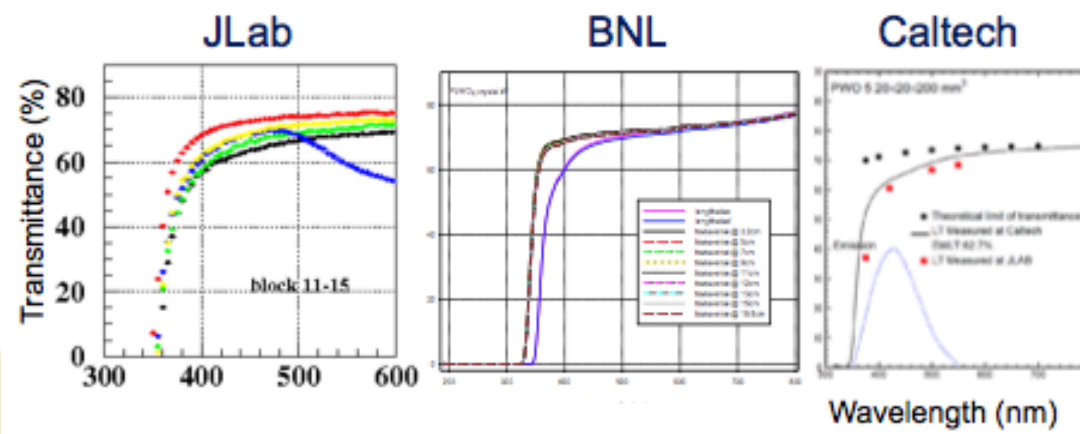




Quality tests of 2014 produced SIC PWO crystals



- ❑ *Preliminary tests carried out at JLab, Caltech, BNL, and Giessen* suggest that:
  - ➢ Crystals are of better quality than previous ones
  - ➢ A subset of the crystal samples is consistent with CMS quality standards *[IEEE Trans.Nucl. Sci. NS-51 1777]*



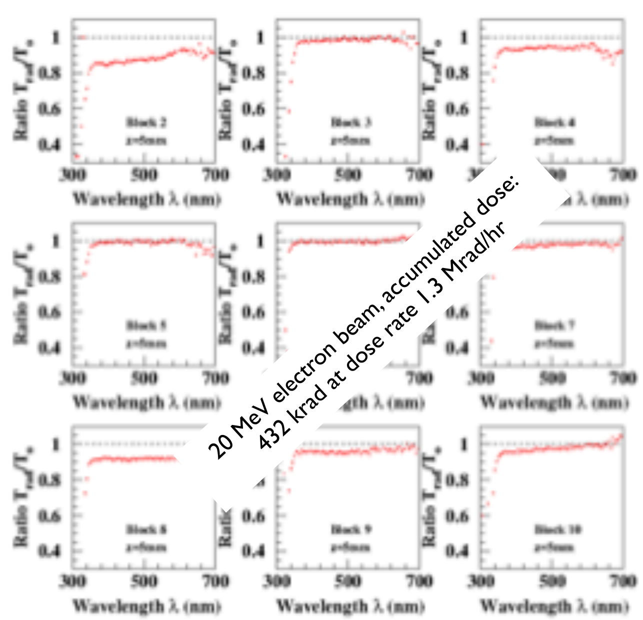
Systematic differences between setups

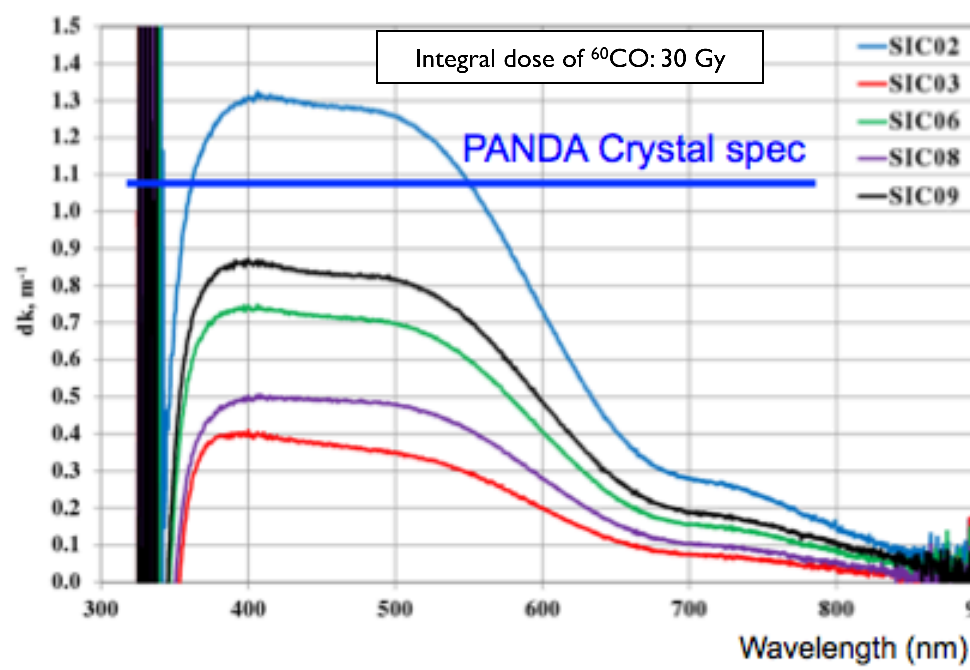
❖ Still need to determine crystal homogeneity

❖ Setup dependent systematic effects under study

- ❑ *Preliminary results* from irradiation with beam in Idaho and *initial tests* of a subset of crystals in Giessen suggest that crystals have high radiation resistance

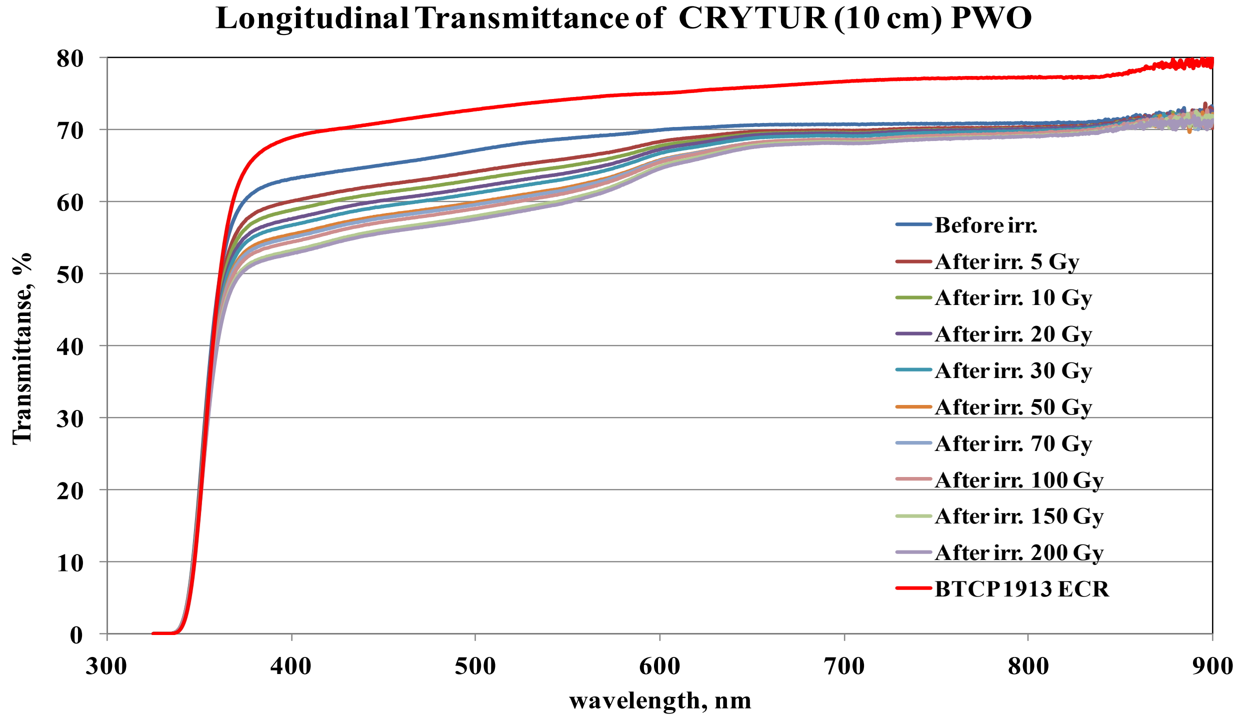
❖ Further tests to better understand radiation damage effects underway

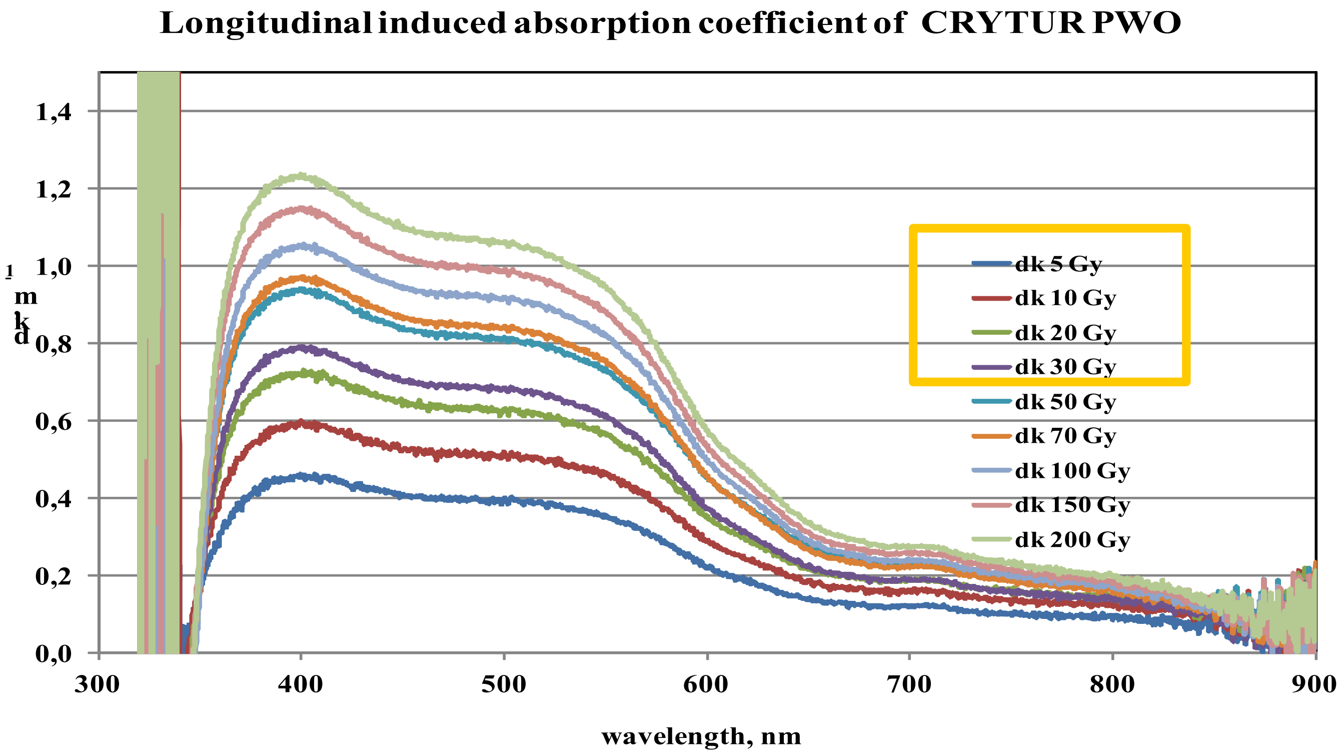




Status of CRYTUR Crystal Production

- ❑ First full-size crystal produced with size 2x2x20cm^3
  - ➢ Produced using raw material from BTCP
  - ➢ Some longitudinal inhomogeneity
- ❑ Results of optical and radiation hardness studies suggest that:
  - ➢ Transmittance falls within 8% of the BTCP crystals at 420 nm
  - ➢ Crystals have sufficient light yield
  - ➢ Crystals are radiation hard for dose rates go up to 100 Gy (spec: 30 Gy)
- ❑ Status at CRYTUR:
  - ➢ Infrastructure upgrades expected mid-July; production in August
  - ➢ Pre-paid orders of R&D crystals from Giessen and Uppsala

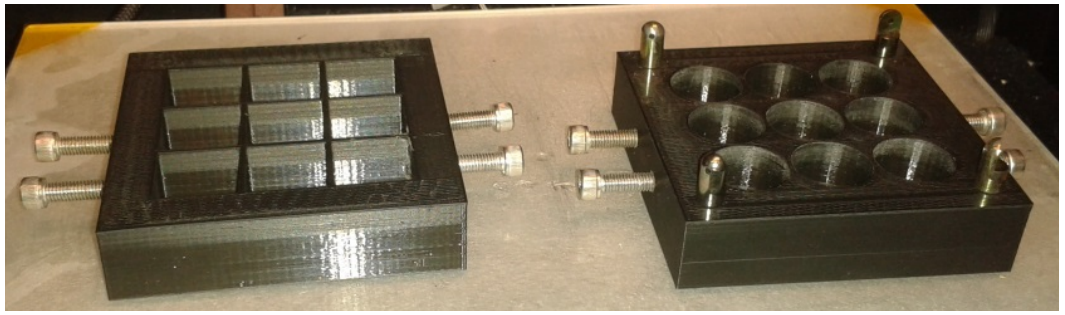


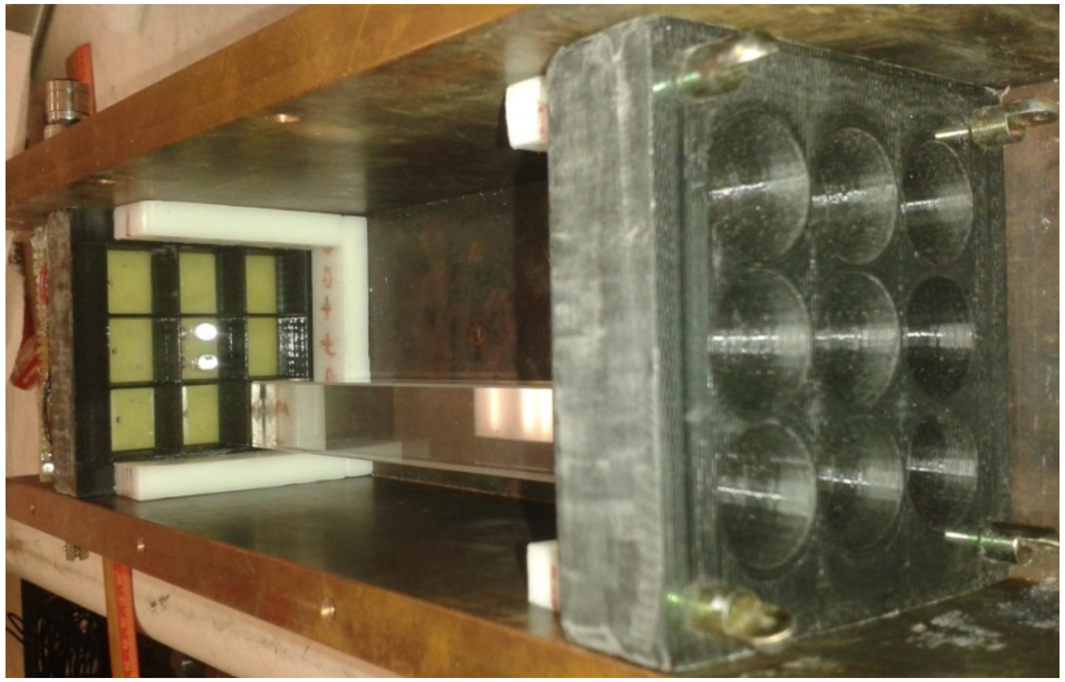


Plans for FY16

- ❑ Complete infrastructure for crystal testing at, e.g., IPNO and understand systematic effects in the characterization of SIC crystals
  - ➢ Synergistic with independent research for the Neutral Particle Spectrometer project at JLab
    - ❑ As part of this project a set of SIC crystals has been investigated
      - ❑ Test setup including optical properties and crystal homogeneity is being developed at CUA

This is an essential aspect to quantify homogeneity of crystals produced at SIC





Neutral Particle Spectrometer prototype produced with 3D printing technology

- ❑ Procure full-sized crystals from Crytur and evaluate crystal-to-crystal variation

- ❑ Construct a prototype to study the crystals in test beam and measure the actual energy and position resolution – also allows for testing a SiPM-based readout

These measurements would provide additional important information on crystal specifications and their impact on EIC detector performance

Future Plans

General Goals: Optimize geometry, cooling, temperature stabilization and choices of readout system of the endcap inner calorimeter

- Explore how temperature stabilization could be achieved for the inner endcap calorimeter for EIC
  - Cooling and choice of temperature and its stabilization are important aspects for crystal calorimetry. The choice of temperature balances light output and radiation recovery.

- Explore if cooling is the optimal choice to reduce readout noise and if it is how to implement such a system.
  - Our initial studies with a SiPM-based readout have shown significant effects of noise at room temperature emphasizing the need for cooling.
  - Cooling techniques have been explored for PANDA and CMS. The type of cooling and avoiding condensation depend to some extend on environmental factors

Summary. Ongoing calorimeters R&D:

- Progress was made in all areas of calorimetry R&D planed for 2015.
- Proposal to continue ongoing R&D for BEMC sampling Emcal and Crystals (PWO) for a second year in 2016 as was originally planned.
- R&D with readout sensors will continue.
- Some of intermediate term goals (~2018) for calorimeter consortium start to crystallize with a concrete proposal under discussions for the next funding cycle.

Budget request for FY2016 (details in backup slides):

W/SciFi EMCal Development Teams (UCLA team $101.8 k, BNL team $27 k)	$128.8 k
SiPMs Test and Evaluation	$23.0 k
PWO Development Team	$75.0 k
Shashlyk EMCal Team	$60.2 k
Total	$287.0 k

Next is new proposal presented by

X. Zheng (UVa)

Simulation and Construction of Shashlyk-Type Ecal for the EIC

Xiaochao Zheng, Nilanga Liyanage, Vincent Sulkosky

University of Virginia

Guy Ron

Hebrew University of Jerusalem, Israel

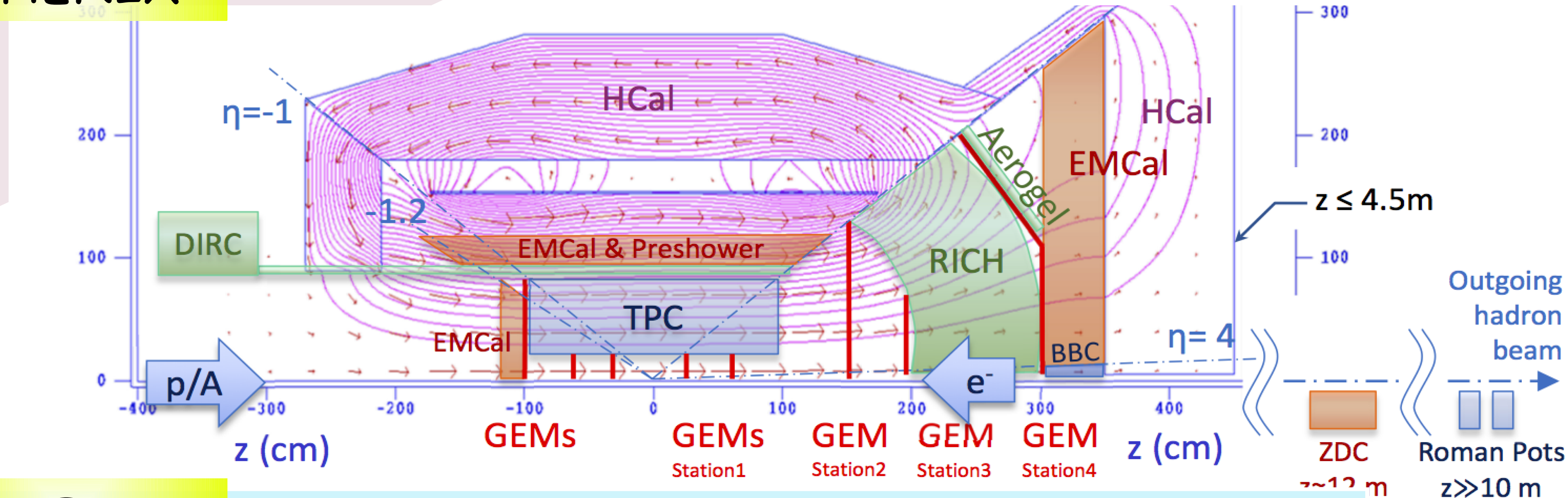
W. Deconinck

College of William and Mary

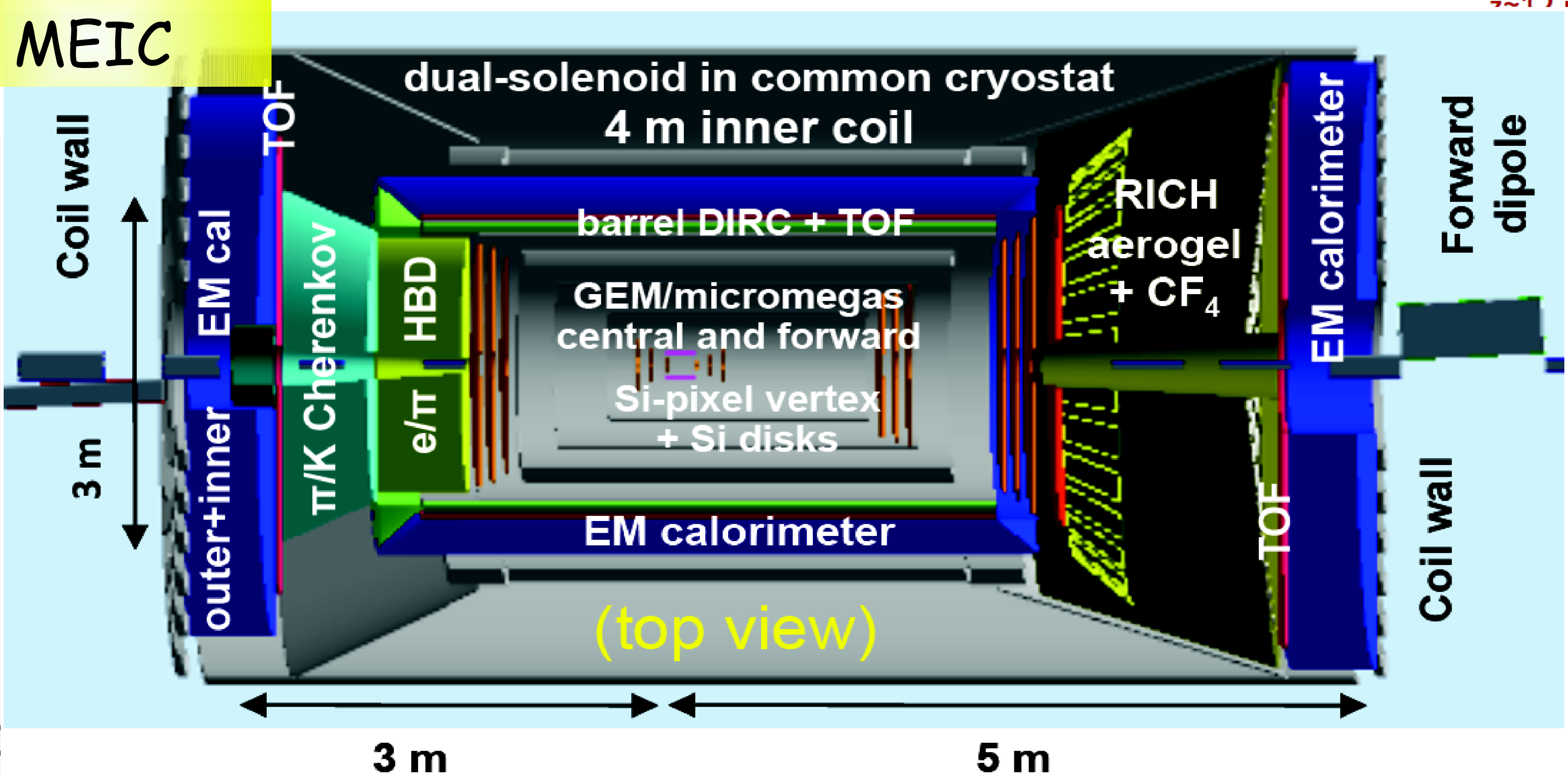
Alexandre Camsonne (Jefferson Lab), CunFeng Feng (Shandong University, China), Jin Huang (Brookhaven National Lab), Tim Holstrom (Longwood University), Zhiwen Zhao (Duke University)

Ecal Needs for EIC

ePHENIX



MEIC



Ecal Needs for EIC

1. Electron-direction Ecal: need (1-2)%/sqrt(E) for inner radial region, top choice is crystal; (5-6)%/sqrt(E) for outer radial region.
2. Hadron-direction Ecal: planned (12-15)%/sqrt(E) for ePHENIX and (5-6)%/sqrt(E) for MEIC.
3. Central Ecal: need 12%/sqrt(E), need to be radially compact (25cm), current top choice is W-scifi.

Radiation background at colliders: must sustain up to 10^6 rad

Possible Use of Shashlyk Ecal for EIC

1. Electron-direction Ecal: need (1-2)%/sqrt(E) for inner radial region, top choice is crystal; (5-6)%/sqrt(E) for outer radial region – shashlyk may be the best choice
2. Hadron-direction Ecal: planned (12-15)%/sqrt(E) for ePHENIX and (5-6)%/sqrt(E) for MEIC. – shashlyk may be the best choice
3. Central Ecal: need 12%/sqrt(E), need to be radially compact (25cm), current top choice is W-scifi (need to study if shashlyk is possible)

Radiation background at colliders: must sustain up to 10^6 rad

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3. Central Ecal: need 12%/sqrt(E), need to be radially compact (25cm), current top choice is W-scifi (need to study if shashlyk is possible)

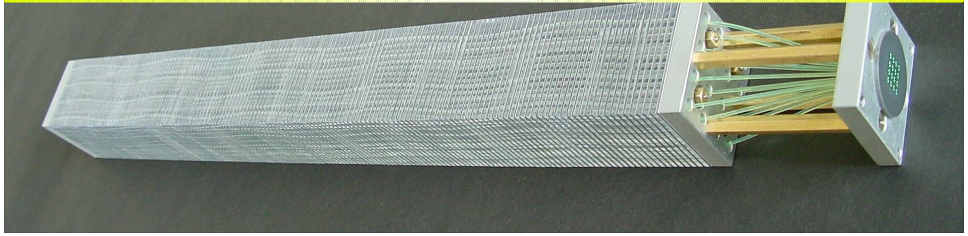
Module shape: all do not need to be projective, however

- central: projective shape highly desired for sPHENIX
- electron- and hadron-direction Ecals, projective design will help with PID performance.

Snapshots of Shashlyk Ecal Technology

- thin layers of absorber stop particles while thin scintillator layers samples the shower signal
- light guided out by WLS fibers
- radiation hard (10^6rad), more cost effective than crystals such as LSO, energy resolution can reach 5%/sqrt(E) or even lower.

IHEP, COMPASS Shashlik, 2010



Developed for COMPASS, KOPIO experiments, and used by ATLAS, ALICE, CMS upgrade

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- Technology relatively mature, but construction expertise is dominated by IHEP&ITEP (Russia). Only a couple of US groups have constructed Shashlyk modules (e.g. ALICE — Wayne State U., U. of Iowa)
- scintillator parts by injection molding and lead sheets by stamping, mold and tooling cost ~$45k, dominate prototyping cost
- difficult to construct projective-shape modules
- requires intensive manual labor during assembling process

Our Focus for the first year

- Study preliminary design of shashlyk Ecals for EIC's outer electron and hadron Ecals, look into central Ecals.
- Look into possible re-use of existing or planned Shashlyk modules for EIC
- To gain knowledge and hands-on experience with testing shashlyk module components, focusing on testing 3D-printed scintillators

The “New” Component — 3D Printing

- Three existing 3D printing methods:
  - FDM
  - Resin-printing (polyjet)
  - metal printing

- We have already experimented with Polyjet-printing scintillators [G. Ron (Hebrew U.), W. Deconinck (W&M)]
  - Published results show plausible light yield (30% of commercial polysterene-based scintillators, currently improving compound design, comparable to commercial, need more study)
  - Also need data on optical transparency, mechanical strength, stability, radiation hardness

3D-printed scintillator at W&M

http://arxiv.org/abs/1406.4817

Potentials of 3D Printing

- fast and cost-effective prototyping;
- "easy" construction of projective shape modules;
- may provide better layer thickness uniformity → better energy resolution;
- possible simplification of assembly process.

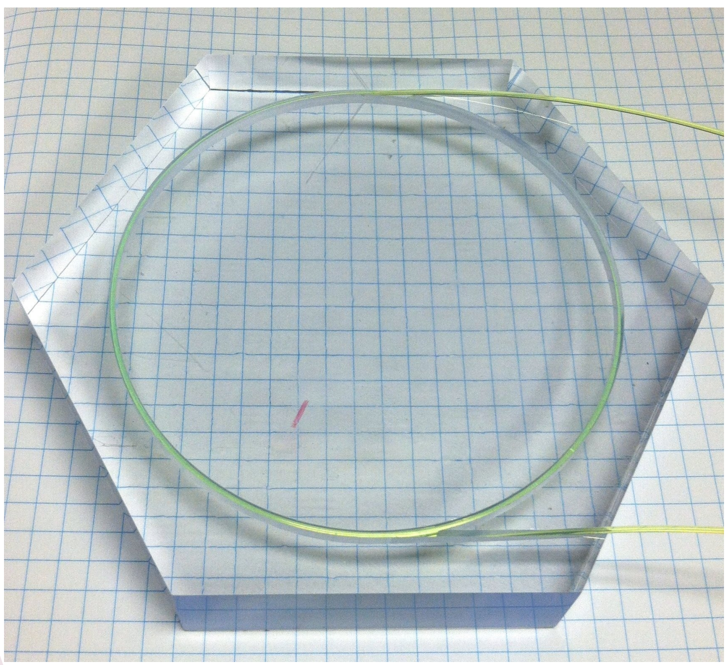
Test Plan for the First Year

- Obtain 3D-printed scintillator samples from Stratasys(Isarel), or made in-house at W&M
- Study light yield, transparency, mechanical properties (<u>compressive strength</u>), radiation hardness → revise compound formula and iterate
- *[Many of these studies are valuable for shashlyk module construction (quality screening of parts) regardless of whether 3D-printed sci works]*

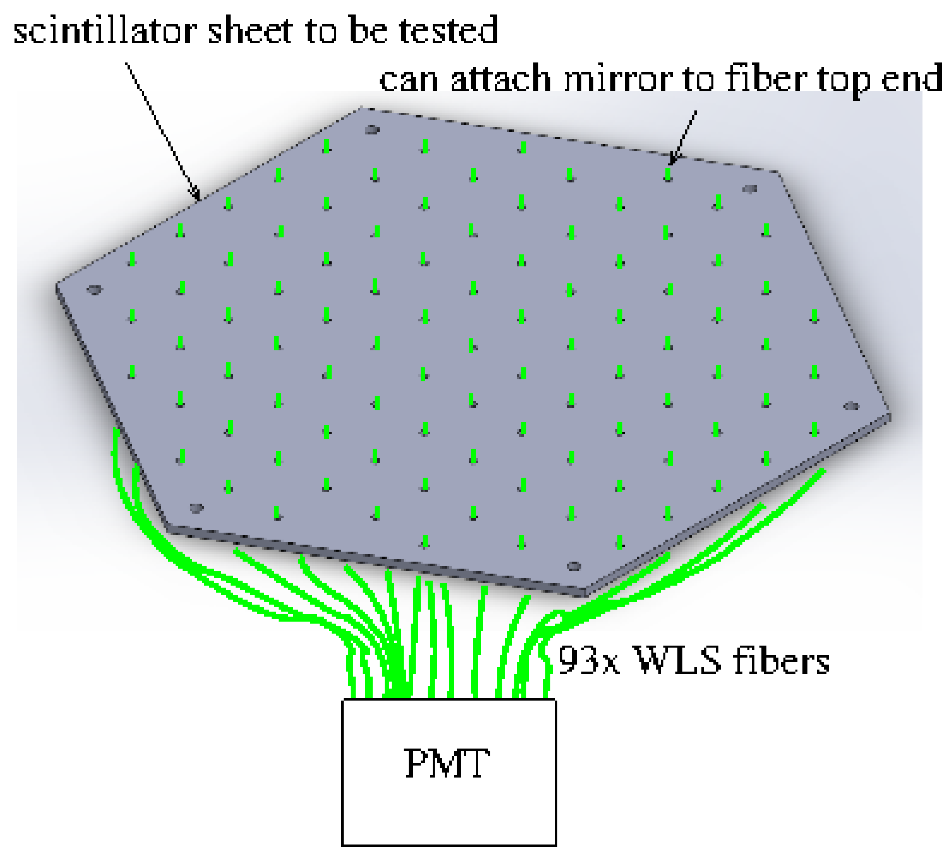
Test Plan for the First Year

- For mechanical testing: simple shape first, then shashylk components

- SoLID Preshower samples 20-mm (regular scintillator) tested at UVa, 2 vendors/bases – polysterene, phenylethene; will also test PVT-based



- Shashlyk components (1.5mm)



Will also study 3D-printed light guides using t-glase (a commercially available "optical quality" material), useful for light guides with complicated shape.

Budget

Item	cost
5 Eljen EJ-205 shashlyk sheets	$1,570
5 Beijing HE-Kedi shashlyk sheets	$1,000*
10 lead layers (Kolgashield) for the combined mechanical test	$800
Simple-shape scintillators as references (Eljen)	$1,000*
Light guides as references (Eljen)	$1,000*
Two scintillator bars (Eljen) for triggering the cosmic test	$1,400
Readout PMTs for the cosmic test (2 R11102)	$800
Other material and supply	$2,000
Travel	$1,000
One quarter postdoc support (incl. 28% F.B.)	$17,910
Graduate student, one-half A.Y. stipend	$19,158/2=$9,579
Total Request (direct only)	$38,059
Total Request (including 58% UVa F&A cost)	$60,133

may include shashlyk scintillators from China ($500 for 10), but also possible Chinese contribution

- The postdoc will focus on simulation/design, lead the radiation hardness test, and guide the graduate student;
- From other UVa resource: FDM/t-glase for printing light guides; make Tungsten-filled FDM filament for printing absorber sheets.

Future Plan

- Prototyping for EIC's Shashlyk Ecal and test its performance, but whether 3D printing can be used will depend on results from the first year.

Backup Slides.

Energy Resolution from Shashlyk Ecals

Experiment	ALICE	COMPASS	JLab SoLID simulation	PANDA	KOPIO
Pb layer (mm)	1.44	0.8	0.5	0.3	0.28
sci layer (mm)	1.76	1.5	1.5	1.5	1.5
Energy Res. a/sqrt(E)	11%	6.5%	5.8%	~3%	3.5%
Rad. length X_0 (mm)	12.3	17.5	24	34	35
Total length in X_0	20.1	22.5	18	20	16

- (5-6)%/sqrt(E) can be achieved with shashlyk technique, better resolutions possible.

Material	ρ g/cm^3	X_0 cm	R_M cm	λ_I cm	n refrac.	τ ns	peak λ nm	light yield	Npe /GeV	rad	$\delta E/E$
Crystals											
NaI(Tl)	3.67	2.59	4.5	41.4	1.85	250	410	1.00	10^6	10^2	$1.5\%/E^{1/2}$
CsI	4.53	1.85	3.8	36.5	1.80	30	420	0.05	10^4	10^4	$2.0\%/E^{1/2}$
CsI(Tl)	4.53	1.85	3.8	36.5	1.80	1200	550	0.40	10^6	10^3	$1.5\%/E^{1/2}$
BGO	7.13	1.12	2.4	22.0	2.20	300	480	0.15	10^5	10^3	$2\%/E^{1/2}$
PbWO4	8.28	0.89	2.2	22.4	2.30	15/60%	420	0.013	10^4	10^6	$2.0\%/E^{1/2}$
LSO	7.40	1.14	2.3		1.81	40	440	0.7	10^6	10^6	$1.5\%/E^{1/2}$
PbF2	7.77	0.93	2.2		1.82	Cher	Cher	0.001	10^3	10^6	$3.5\%/E^{1/2}$
Lead glass											
TF1	3.86	2.74	4.7		1.65	Cher	Cher	0.001	10^3	10^3	$5.0\%/E^{1/2}$
SF-5	4.08	2.54	4.3	21.4	1.73	Cher	Cher	0.001	10^3	10^3	$5.0\%/E^{1/2}$
SF-57	5.51	1.54	2.6		1.89	Cher	Cher	0.001	10^3	10^3	$5.0\%/E^{1/2}$
Sampling: lead/scintillator											
SPACAL	5.0	1.6				5	425	0.3	2×10^4	10^6	$6.0\%/E^{1/2}$
Shashlyk	5.0	1.6				5	425	0.3	10^3	10^6	$10\%/E^{1/2}$
Shashlyk(K)	2.8	3.5	6.0			5	425	0.3	4×10^5	10^5	$3.5\%/E^{1/2}$

Budget

	FY16 by Quarters				FY17 by Quarters				FY18 by Quarters			
Deliverable	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Procure crystals from Crytur	X	X	X	X	X	X						
Crystal quality tests	X	X	X									
Radiation Damage studies	X	X	X									
Construct prototype			X	X	X	X						
Test prototype							X	X				
Calorimeter configuration								X	X			
Cooling system studies										X	X	X
Readout system							X	X	X			
Readout noise reduction										X	X	X

Institution	FY16 ($K)	FY17 ($k)
CUA	20	30
JLAB		
BNL	10	20
Caltech	10	
IPN Orsay	35	50
Yerevan		
Total	**75**	**100**

W/ScFi related R&D budget request.

Budget Request for FY2016

Hamamatsu H6559 PMT assemblies (2)	$2.5k
Kuraray 3HF and SCSF78 fibers	$10k
Tungsten Powder	$7k
Hamamatsu S8664-1010 APDs	$15k
Hamamatsu MPPC	$2.8k
Supplies (Epoxy, etc.)	$5k
Machine Shop (26% overhead included)	$12.6k
Travel (FNAL test run, EIC meetings)(26% overhead included)	$18.9k
Support for undergraduate students (26% overhead included)	$12.6k
SENSL SiPMs for new Sc. Hodoscope	$3k
CMC080 qADC (2 x 16 channels)	$8k
FEEs for APD readout (components only)	$3k
PS300 Power Supply (APD bias)	$1.4k
Total Direct	$92.7k
Total	$101.8k

BNL Team – $27k